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# Bulletin volcanologique

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## l'Association de Volcanologie

### de l'Union géodésique et géophysique internationale

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FRANCESCO SIGNORE

Série II — Tome III

B. V.



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(Voir la suite à p. 3 de la couverture)

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Pour toute communication relative au Secrétariat général de l'Association internationale de Volcanologie, adresser: Prof. FRANCESCO SIGNORE,
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Téléph. 15749

*( Pubblicato in luglio 1938 )*

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H. M. GEOLOGICAL SURVEY, SCOTLAND

# The rhythmic eruptions of Ben Hiant, Ardnamurchan, a Tertiary volcano

*(With 6 fig. and 3 plates)*

## I. — Introduction.

The mountain of Ben Hiant, sea-girt on two sides, is conspicuous in its isolation. Inland its rock-clad slopes rise abruptly from comparatively low ground. Seawards it is bounded by dark cliffs along the flanks of a rugged headland called Maclean's Nose, at the junction of Loch Sunart with the Sound of Mull. Though it is less than 2,000 feet in height, sections of Tertiary explosion-vents are provided which are probably the finest in Scotland (Plate I).

Geological mapping has shown that the mountain consists of a group of two or three volcanic vents, mainly filled with agglomerate and tuff, together with the remnants of their bounding walls, and of a transgressive intrusion of quartz-dolerite which forms the central peak (Fig. 1). The older rocks that bound the vents comprise flat-lying Tertiary basaltic lavas resting upon a thin development of Mesozoic strata or directly upon Moine Schists. They are best exposed along the seaward slopes, where two orifices have been recognised, a north-eastern vent and a later south-western vent. Both vents are elongate in ground-plan, with their longer axes arranged tangentially in relation to the earliest intrusion-centre of the Ardnamurchan series (Centre 1). They lie along the outer side

of the complex of vents and intrusions referred to this centre.

The vents are seen to traverse only the basal portion of the basaltic plateau. They are presumably later than

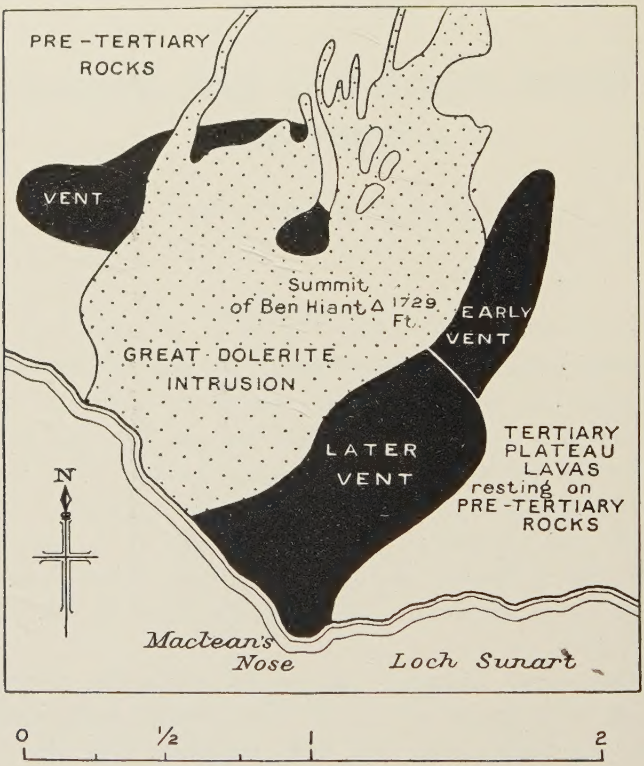


Fig. 1.—Sketch-Map of Ben Hiant.

the plateau-lava period, mainly because no intercalations such as trachytic tuffs which might have been derived from Ben Hiant are found in the immensely thick lava-plateau of the adjoining island of Mull. Though the vents would thus seem to mark the beginning of a new phase, they are nevertheless linked with the basaltic period in two ways. Trachyte, a world-wide associate of olivine-basalt, is their common rock-type, and, as certain tuffs in the vents and

salo a plug that cuts the pyroclastic materials clearly show, a magma approximately of the composition of a felspar-phyric basalt, sometimes olivine-bearing, was also involved.

The materials that now fill these two great explosion-craters are exposed mainly at levels on the hill-sides intermediate between the denuded margins of the vent-walls and the central doleritic intrusion (Plate 1). Only near Maclean's Nose has the wall that bounds the later vent been eroded down to sea-level. Cliffs of volcanic agglomerate and tuff just east of the promontory constitute, as it were, a partial cast of the later crater. These cliffs, and a stream-gully cut in the grass-covered slope just above, furnish the main subject for the present investigation.

## II. — The great craters.

A feature of the agglomerates of Ben Hiant is the absence, or extreme rarity, of fragments of the country rocks that form the vent-walls, except in the vicinity of the walls, where a scree of basalt-lava blocks accumulated. This is a contrast to the inner circle of vents belonging to Centre I, the so-called Northern Vents, in which fragments of Moine Schists, Mesozoic sediments and basalt lava are ubiquitous. Each of the Ben Hiant craters, it is concluded, was completely cleared of country rock by a stupendous explosion or series of explosions, and was then filled in with materials which were mainly derived from the volcano itself.

The size of the crater-cavities must have been truly enormous. In the case of the later vent an alternating succession of flat-lying or gently inclined beds of agglomerate and tuff, with occasional lavas of andesitic pitchstone, abuts against a vertical bounding wall (Fig. 2). This succession extends from sea-level up to a height of 1,200 feet on the mountain, where it terminates against the intrusive margin of the central mass of dolerite. The cavity therefore must have been at least 1,200 feet in depth. It may have been much deeper, since the plateau lavas through

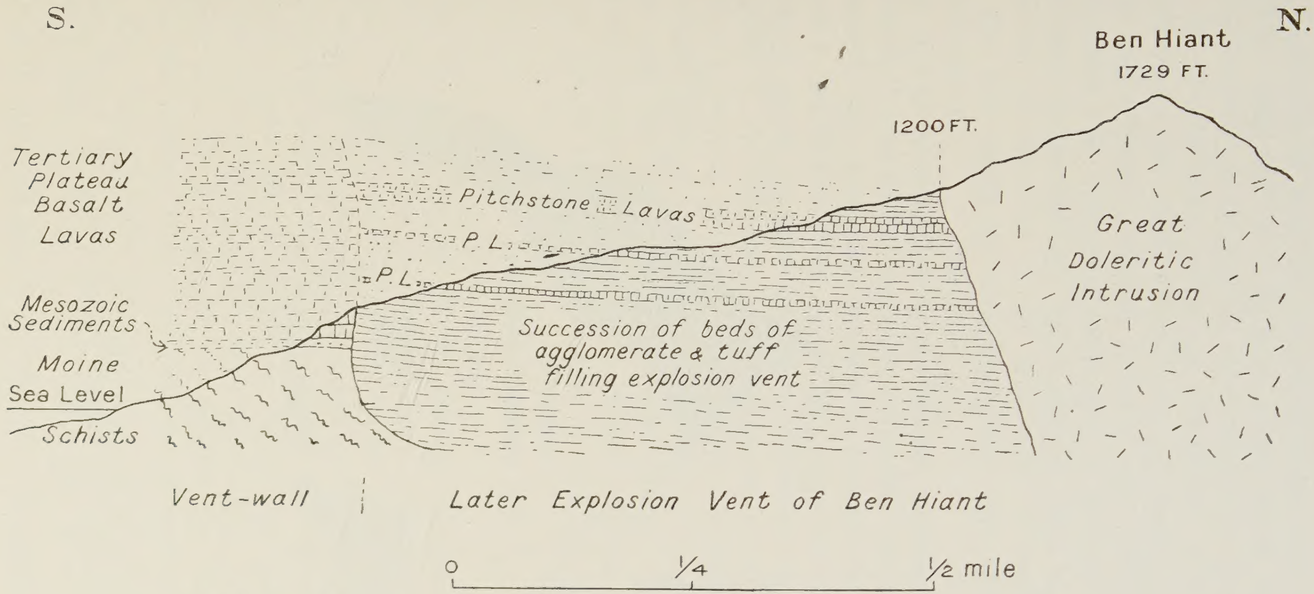


Fig. 2. — Horizontal Section illustrating the Later Explosion - Vent of Ben Hiant (small intrusions in vent are omitted).

which the vent was drilled attain a thickness of 5,000 to 6,000 feet in the adjoining island of Mull, and over Ardnamurchan the lava-plateau may well have been at least half this amount. Blocks of « big-felspar » basalt in the vents may have been derived from a lava-zone which, in Mull, occurs 2,000 ft. above the base of the basaltic plateau [1]). During the post-plateau explosive period some such amount of cover must have been pierced, and wide and deep volcanic craters laid open to the sky. Further, as in the case of Vesuvius, inaugurated by the partial destruction of Somma, the later crater of Ben Hiant was blown in part out of the earlier vent, and perhaps through a volcanic cone that rose around the earlier orifice (Fig. 5). No cone materials however are preserved.

## III. — **The contents of the craters.**

Along the cliffs east of Maclean' s Nose and in the gully cut by a stream in the slope above, the internal structure of the vent-infillings is especially well displayed. During the original survey of the district, in 1921, it was noted here with particular clearness that beds of unsorted agglomerate were separated by thinner bands of tuff of very fine texture [2]). It is now claimed that each bed of agglomerate with its overlying bed of tuff represents the products of a distinct volcanic eruption. Their combined thicknesses are on an average 20 to 30 feet. Since the observed thickness of the vent-infilling is 1,200 feet, some 50 eruptions seem to be indicated.

The magma concerned in the explosive phase was mainly intermediate (trachytic) in composition. The prevalent trachytic blocks in the agglomerates bear witness

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1) Richey J. E., « *Guide to the Ardnamurchan Model* », Mem. Geol. Surv., Gt. Brit., 1934, p. 21.

2) Richey J. E., in « *The Geology of Ardnamurchan* » *etc.*, Mem. Geol. Surv. Scot., 1930, pp. 125-7.

to this fact [1]). Magmas of various other kinds were involved. Their products include lava-flows of andesitic pitchstone (inninmorite), which are interbedded with the pyroclastic materials. occasional fragments of rhyolite in both agglomerates and tuffs, recurring small pieces of light grey or brown subvitreous or vitreous rocks in the tuffs, and a plug of felspar-phyric dolerite.

The ubiquitous trachyte fragments are sometimes scoriaceous, but they are all angular, with surfaces due to fracture.. They represent magma which consolidated in the volcanic pipe or its vicinity. and which was broken up by explosion. The term, agglomerate, has been applied by all recent British writers to our Tertiary pyroclastic rocks of coarse texture, and the practice is continued in the present paper. In the terminology for pyroclastic rocks which was suggested a few years ago by Wentworth and Howel Williams, [2]) the Ben Hiant agglomerates would be classed as « volcanic breccia, accessory », or in some cases, as « tuff breccia, accessory », the qualifying word « accessory » indicating the dominantly cognate origin of the materials.

It may be urged here that in the constant repetitions unavoidable in a paper the use of the term « agglomerate » to denote coarse pyroclastic materials has the advantage of brevity, and with an accompanying description its particular meaning can be made clear.

Although fragments of country rocks are absent from the agglomerates, with the possible exception of the blocks of « big felspar » basalt, two slices made from tuffs showed many small particles of quartz and white mica [3]). The Moine Schists have been already suggested as the most probable source for these minerals. Yet how could these

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1) For more details concerning the composition of the agglomerates see Thomas H. H. in « *The Geology of Ardnamurchan* » etc., Mem. Geol. Surv. Scot., 1930, pp. 133-6.

2) Wentworth C. K. and Howel Williams, « *The Classification and Terminology of the Pyroclastic Rocks* », Bull. Nat. Research Council, N. 89, Washington, 1932, pp. 51-2.

3) Thomas H. H., in op. cit., 1930, p. 136.

country rocks come to be comminuted during the later stage of an eruption represented by the tuff-beds, and not be represented by fragments in the underlying agglomerates! A suggestion to explain the puzzle was put forward recently, namely, that gas-erosion of the volcanic pipe supplied these materials to the tuffs [1]). Such an application of the well-known effect observed by Dr. F. A. Perret during the eruption of Vesuvius in 1906 could only be tentatively made with the scanty evidence then available. Further investigation was therefore undertaken last spring (1937), and many more specimens of the tuffs were collected for study.

## IV. — Field relations and composition of the tuffs in the gully.

*Field Relations.* — The tuff-seamed agglomerate cliffs east of Maclean's Nose are for the most part inaccessible to the geologist, and only their base can be reached conveniently. Consequently the stream-gully that traverses the slope above was chosen for detailed examination. Here a pitchstone lava, inclined into the hill at a low angle, overlies a succession of interbedded tuffs and agglomerates which extend downstream for 160 yards to where a vertical vent-wall of basalt lavas intervenes. The beds of tuffs are thicker than along the cliffs, and this appears to be the main reason for the difference in topography between the cliffs, formed mainly of coarse agglomerates, and the grassy slope above, floored mainly by tuffs and fine agglomerates.

The succession seen in the gully is given in Fig. 3. Between the vent-wall and the base of the pitchstone lava four distinct eruptions are recognised in four pairs of beds of unsorted agglomerate and tuff. Sharp junctions separate the tuffs from the overlying agglomerates. The contacts

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1) Richey J. E., «*Some Features of Tertiary Igneous Activity in Scotland and Ireland*», Bulletin Volcanologique, Série II, Tome I, 1937, p. 34.

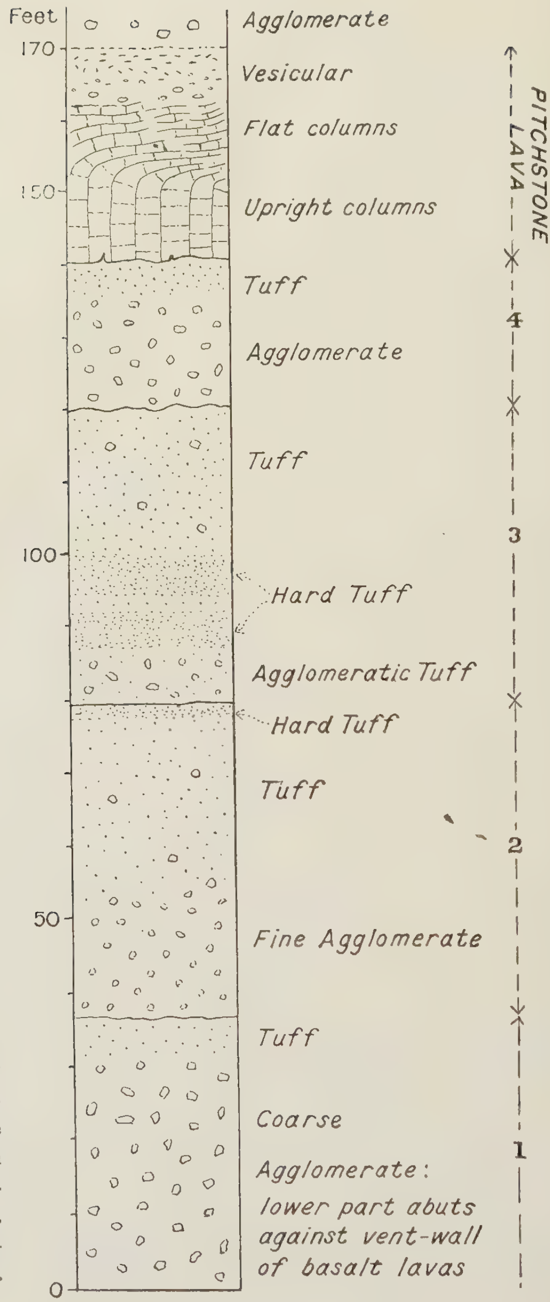


Fig. 3.

Vertical Section of Tuffs and Agglomerates below the lowest Pitchstone Lava in the Later Vent of Ben Hiant, in stream-gully 2/3 ml. S. 15° E. of the summit of Ben Hiant.

can be located without difficulty. The more easily weathering tuffs are surmounted by slightly projecting outcrops of agglomerates, and their junctions are perfectly clean-cut. In contrast, the beds of agglomerate grade upwards, as a rule rapidly, into tuff. Similar relations, it may be emphasized, are seen along the agglomerate cliffs (*see* Pl. II, Fig. 1) and elsewhere on Ben Hiant.

The blocks in the agglomerates are of various sizes. Nine inches to a foot in length is a usual measurement for the larger fragments. These are set in a matrix either of smaller fragments or, as in 3 of the figure, mainly of fine tuff. The great majority are dark grey trachytes usually without felspar phenocrysts, but trachytes light in colour and with conspicuous porphyritic felspars are common in places. Some contain abundant vesicles, but there are no typical bread-crust bombs. Large blocks of « big-felspar » basalt, common elsewhere at many levels in the later vent, are absent from the stream-section. Small fragments, however, are found. The agglomerates of the gully are on the whole much less coarse than those, for example, immediately below them along the cliffs.

The tuffs are very fine grained rocks. Their grain size may equal that of a fine sand, with particles about 1/3 mm. in diameter. Usually their texture is comparable with that of a mud, with particles about 1/20 mm. in diameter, and originally they were simply volcanic dusts. Following the classification given by Bailey T. L. [1]), they may be termed sand-tuffs and dust-tuffs. They usually weather into fine rock-rubble, but a solid medium-grey tuff which breaks with a conchoidal fracture is an exception to this rule. It occurs as a definite bed at the top of 2 and again in the middle of 3. Fragments of trachyte etc., up to about 8 inches or so in length, are usually sparsely scattered through the deposits of tuff.

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1) Bailey T. L., «*The Gueydan, a New Middle Tertiary Formation from the Southwestern Coastal Plain of Texas*», Univ. Texas Bull., N. 2645, 1926, p. 109.

Some further details of the succession given in Fig. 3 may be added.

In 1, typical coarse agglomerate with blocks of non-porphyritic and felspar-phyric trachyte, etc., from a foot or so in length down to small fragments, is succeeded by a relatively thin bed of dark ochreous-weathering tuff which contains many small angular pieces of basalt, trachyte, etc. In a slice of the tuff examined under the microscope a tiny fragment of typical quartzose Moine Schist was found - the only occurrence of this rock which has been detected in the Ben Hiant vents (Plate III, Fig. 4). In addition to quartz and felspar the rock contains an altered mica and sparse tiny crystals of colourless garnet.

The junction with 1-2 is sharp and slightly irregular.

In 2, fine, mainly trachytic, agglomerate grades upwards into tuff with occasional fragments (a dyke crosses the stream here). At the top comes a hard band of tuff with conchoidal fracture.

The junction with 2-3 is sharp and even.

In 3, tuff predominates. Only the lowest part could be styled agglomerate, and here tuff forms a matrix in which are set the fragments of non-porphyritic trachyte, etc. Hard conchoidally-fracturing tuff follows in two separate beds which extend along the eastern side of the gully. The reason for its distinctive characters is not known. No differences could be seen in microscope sections between the hard tuffs and the prevalent softer varieties, such as occur above, containing scattered angular blocks mainly of non-porphyritic trachyte.

The junction with 3-4 is clean-cut, but is highly irregular.

In 4, the agglomerate is somewhat fine, being mainly composed of abundant, small, angular fragments. Small fragments are also found in the overlying tuff. Just below the pitchstone lava the tuff is hardened by contact-action and forms a slight shelf along the gully near stream-level. Narrow wedge-like portions of the tuff extend into the

base of the lava, as though the lava as it flowed along had pushed up some of the tuff here and there.

The pitchstone lava has been described in detail in the Geological Survey Memoir on Ardnamurchan. Perhaps most remarkable in the present connection is the fact that fragments of pitchstone are not found as such in the agglomerates. Possibly fragments may have escaped detection owing to devitrification having altered their appearance.

*Composition of the Tuffs.* — A dozen specimens of tuffs from the gully and from the cliffs below have now been sliced. All may be classed as lithic varieties, though they invariably contain a considerable amount of broken crystals of various origins and vitreous or semi-vitreous particles. In keeping with the original observation of Thomas H. H., quartz is an ingredient (Plate III, Fig. 2). Tiny flakes of white mica are also found, though in small amount. Garnet has now been detected. None could be seen in the slices, but in a heavy residue separated in bromoform from a somewhat coarse tuff, with a grain-size equal to that of fine sand, several clear isotropic grains with a high index of refraction ($< 1.746$) were found. The occurrence of an actual fragment of quartzose felspathic schist with mica and colourless garnet in the tuff at the top of 1, places beyond any reasonable doubt the source of the above-mentioned minerals (Plate III, Fig. 4).

In addition to splinters of quartz, many other transparent colourless broken crystals occur. These are of felspar, mainly plagioclase derived from felspar-phyric basalt, some of it alkali-felspar, including microcline, with little doubt derived from the schists. There is also much dark material, some of it broken augite crystals of basaltic origin, but most of it decomposed greenish basaltic-looking debris. Rarely zircon and large-sized crystals of brown biotite of unknown origin have been noticed. Greenish biotite like that in trachyte fragments is more common.

Grains and tiny fragments in the tuffs which consist of mineral-assemblages or rocks are of no less interest than the mineral grains. Basaltic and trachytic fragments

are common, but sometimes equally abundant is a light-grey rock with a kaleidoscopic variety of texture, which is a quickly cooled product of trachytic or more acid magma. The grains are no larger than the crystal fragments, but spherulitic, microlitic and vitreous or partly vitreous varieties can be easily recognised under a ¼ inch objective. Typical rhyolite is represented by brownish coloured isotropic grains with close-set anastomosing thin dark flow-lines. This rock is remarkable in that it often contains small inclusions chiefly of basalt (Plate III, Fig. 5). Other interesting, more basic types are a golden-brown, probably andesitic glass, and a felspar-phyric andesitic or basaltic rock with an opaque ground-mass presumably rich in iron and probably representing original glass (Plate III, Fig. 7). In the last-mentioned rock the lath-shaped felspar phenocrysts vary much in size even in the same fragment, and often felspar needles centred by inclusions of the ground-mass and with fish-tail ends are interspersed amongst the larger phenocrysts. The felspar varies in composition from oligoclase to labradorite. Occasionally olivine and more rarely augite are also present. A similar rock has been found in the Tertiary vents of Slieve Gullion, N. E. Ireland [1]).

The vitreous grains and pieces in the tuffs are often vesicular, and small broken vesicular fragments recalling certain of Pirsson's vitroclastic forms [2]) are fairly common (Fig. 4). Vitreous or partly vitreous fragments are also sometimes bounded by curved surfaces due to fracture (Pl. III, Fig. 7).

The ingredients of the tuffs are therefore various, and indicate derivation from the following sources :

1. Country rocks : Moine Schists, probably Mesozoic strata (represented by fragment of shale), Tertiary basalt lavas.

[1]) Richey J. E. « *The Tertiary Ring Complex of Slieve Gullion* (Ireland) ». Quart. Jour. Geol. Soc. Lond., vol. 88, 1932, pl. LI, 2.

[2]) Pirsson L. V., « *The Microscopical Characters of Volcanic Tuffs -a Study for Students* » Amer. Jour. Science, vol. 40, 1915, p. 198.

2. Previously solidified vent-magma : represented by well-crystallized trachyte similar to trachyte of the agglomerates, and also perhaps by the glassy rhyolite with flow structure.

3. Vent-magma, probably liquid or partly so at time of eruption : trachytic and also more acid and more basic rocks either vitreous or with incipient crystallizations.

The distinction in composition between the tuffs and agglomerates is thus two-fold. Country rocks and basaltic,

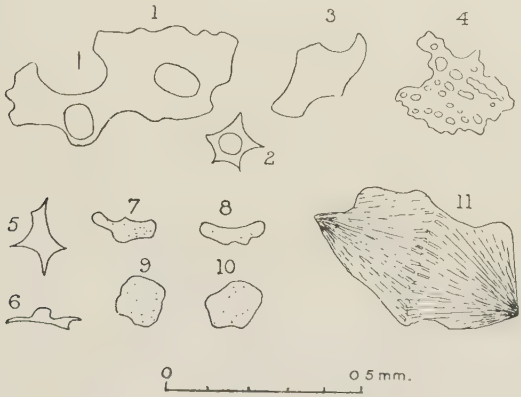


Fig. 4. — Occasional Particles in Tuffs, mainly vitreous.

1- 4, golden brown vesicular glass, intermediate ? andesitic composition
5- 6, clear glass
7-10, grey subvitreous
(9-10, common forms)
11, broken spherulites
acid or trachytic composition.

trachytic and acid magmas have contributed materially to the tuffs. Solid rocks, mainly trachyte, have been broken up to form the agglomerates.

## V. — Suggested mode of eruption.

From the foregoing descriptions two stages in the history of these volcanoes are evident : first, the formation of the initial great cavity ; next, the infilling of the cavity with the products of a series of minor explosive eruptions that were remarkably similar, punctuated in the

case of the later volcano by the outflow of pitchstone lava at long intervals.

Before discussing these stages, two points have to be emphasized. There is reason to suppose that the volcanic pipe was much narrower than the great initial crater. Otherwise the observed disposition of the vent-infillings cannot be explained. Also, high up on the mountain, next to the central intrusive mass of quartz-dolerite, a plug or crater-infilling of felspar-phyric dolerite is partly preserved. It is direct evidence of the existence of a pipe at a level near the top of the 1,200 feet of bedded materials in the later vent. Its diameter would appear to have been about half a mile. A second, related point concerns the source of the vent-contents. It is considered that the craters were filled in with the products of their own eruptions, and not from some outside source such as the Northern Vents. This conclusion is based on two main arguments, the mode of occurrence within the later vent of the pitchstone lavas, and the absence or rarity in the agglomerates of fragments of schist, basalt lava, and quartz-dolerite, all of which are typical of the Northern Vents. The great size of blocks of « big-felspar » basalt in the Ben Hiant vents may also be cited in support of a local origin for the fragmental materials [1]).

*The Initial Stage.* — It is not known at what level the initial explosions originated, since the resultant crater-floor is not visible. It is surmised, as the most probable hypothesis, that magma of great explosive power, highly charged with gas, made its way upwards through the steeply inclined schists and reached the base of the flat-lying basaltic plateau (Fig. 6, 1). There it may have spread out sideways and finally, with the accretion of volatiles from below, have lifted its basaltic cover with explosive violence and shattered it into fragments in a series of gi-

[1]) For examples *see* Plate I, B (Frontispiece), « *The Geology of Ardnamurchan* », etc., Mem. Geol. Surv., *Scotl.*, 1930.

gantic outbursts (Fig. 6, 2). Similar cataclysmic eruptions are of course well known at several modern volcanoes.

In the case of the later vent of Ben Hiant, with certain assumptions, it may be estimated that about a cubic mile of rock was blown into the air. The assumptions are : 1. depth of crater of half a mile (being half the visible thickness of the basaltic plateau in Mull). The depth to which the crater extended downwards into the schists and the thickness of any cone that was formed around the earlier vent are not included. 2. A width of crater of a mile. 3. A length of crater of perhaps two miles. The estimate is probably a low one, partly because the calculated areal measurements of the cavity refer to a section near the bottom of a vent with vertical walls. At higher levels the walls probably had an outward inclination, so that the average areal dimensions of the cavity would be larger than as given above.

The wall of the earlier vent is seen to be inclined. In fact, angles of 30 and 60 degrees have been noted. It is tentatively inferred, in Fig. 5, that the cover broken by the earlier vent consisted of the basaltic plateau only, while that pierced by the later vent included, in addition, an ash-cone built about the earlier orifice. If so, the later initial explosion-cavity must have been much larger than the estimate given above.

After the initial great gaseous eruption ceased, it is assumed that magma of trachytic composition solidified in the pipe and sealed for a time the volcanic throat (Fig. 6, 3).

*The Recurrent Cycle.* — The rhythmic character of the explosive outbursts that followed the initial eruption is suggested by the descriptions already given of the alternating beds of agglomerate and tuff in the vents. The rhythmic succession, agglomerate followed by dust-like tuff, cannot be merely the result of gravity-sorting of the ejactamenta of a single outburst. The larger fragments of the agglomerates are accompanied at the same level by

the tiniest of pieces [1]). The fine-grained tuffs contain blocks as large as the average material in the agglomerates. In one particular case, however, gravity sorting of a shower of ash may perhaps account for a stratified appearance in a bed of tuff [2]). In the main, an explanation must be sought that entails the repeated recurrence of a similar series of conditions in the volcanic pipe. The chief facts to explain are :

1. The textural contrast between the coarse agglomerates and the succeeding dust-like tuffs.

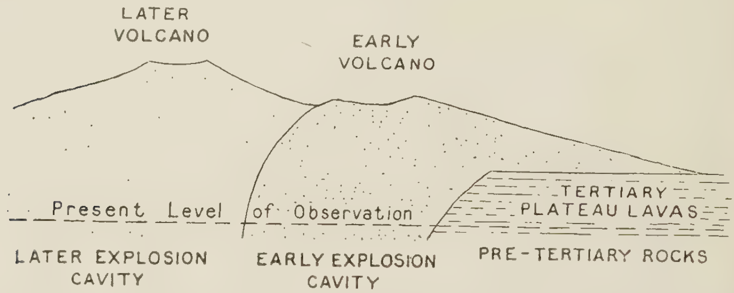


Fig. 5. — The Two Southerly Volcanoes of Ben Hiant: A Reconstruction.

2. The contrast in composition between the agglomerates with their prevalent fragments of trachyte, broken from an already solid vent-rock, and the tuffs with their ubiquitous grains of comminuted Moine Schist and of quickly chilled vent-magmas.

The following explanation is offered.

Beneath the solidifying plug of trachyte, gas from deeper levels would accumulate in the upper part of the magma-column. The solidification of the magma at the top of the magma-column together with influx of gas from deeper levels would result in a progressive rise of the vapour tension. Sooner or later the confining pressure of

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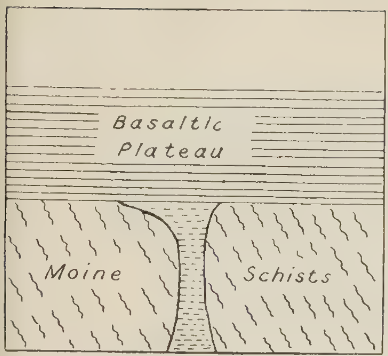
1) See Richey J. E., *op. cit.*, Bulletin Volcanologique, Série II, Tome I, 1937, Pl. I, Fig. 2.

2) See Richey J. E., *ibid.*, Pl. I, Fig. 1.

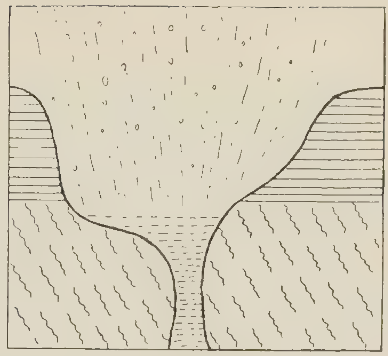
1




**Prelude to Great Initial Eruption**

Magma in pipe reaches base of basaltic plateau, and spreads laterally. Gas pressure at top of magma column increases.

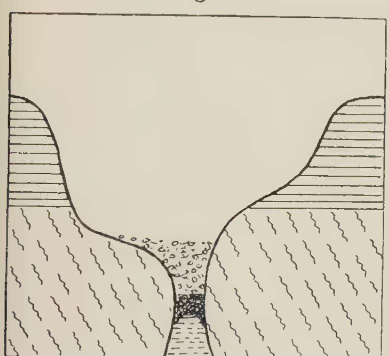
2



**Great Initial Eruption**

Great Explosion-Crater blown out of the basaltic plateau.

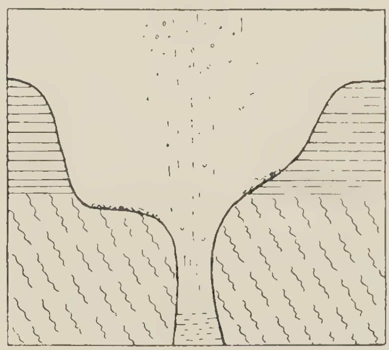
3



**Period of Repose After Initial Eruption**

Top of magma-column solidifies. Top of pipe gets choked with debris. Below solidified plug gas-pressure increases at top of magma-column.

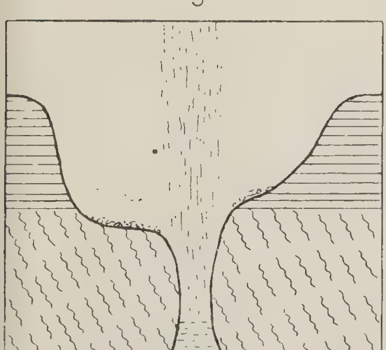
4



**Recurrent Cycle: Activity, First Stage**

Plug is shattered by explosive gases, and is blown out together with other debris. Bed of agglomerate collects on vent-floor.

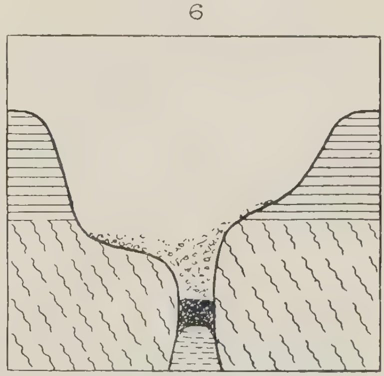
5



**Recurrent Cycle: Activity, Second Stage**

Strong gas-phase causes comminution of materials and erosion of walls of the pipe. Bed of tuff collects on vent-floor.

6



**Recurrent Cycle: Period of Repose**

Top of magma-column solidifies. Top of pipe gets choked with debris. Below solidified plug gas-pressure increases at top of magma-column.

Fig. 6. — Diagrams to illustrate in section the inferred stages in the early eruptive history of a volcano of the Ben Hiant group.

the plug would be no longer sufficient to retain the volatile components in solution. They would therefore escape with explosive violence. The plug, and also whatever debris had collected above it, would be blown out, and a bed of essentially trachytic agglomerate would be spread over the surrounding floor of the crater (Fig. 6, 4).

After this first outburst, a strong gas-phase is envisaged, with the top of the magma-column at some distance below the level of the crater-floor (Fig. 6, 5). Gas-erosion of the walls of the pipe, such as PERRET concluded to have marked the Intermediate Gas Phase of the 1906 eruption of Vesuvius, is taken to explain the occurrence of schist material in the tuffs. At Ben Hiant a considerable volume of magma would seem to have been used up during this stage, since it is represented in the tuffs by diverse vitreous or subvitreous types. The complete intermingling of the various comminuted materials in the tuffs, and the high proportion of the heavier basaltic particles and debris of lava origins, presents no apparent difficulty. The dust would be projected far into the air, and would settle in the crater to form a bed of tuff, to some extent after the main eruption had ceased. Intermingling of materials is what one would naturally expect, while the relative scarcity of light glassy particles may well be due to their having been carried for the most part beyond the environment of the crater.

It is not known in what order the basic to acid magmas which belonged to the tuff phase came into play, but one deduction can be made. Since the agglomerates are mainly composed of trachyte, most of it solid, but part of it scoriaceous, it is inferred that the magma left over in the pipe after any particular gas-phase had ended was of trachytic composition.

The author has failed to find in the literature of extinct volcanoes any record of a similar set of facts to those displayed on Ben Hiant. Comparisons are desirable, to elucidate further, or to correct, the tentative explanation

which Ben Hiant suggests. A difficulty is that the explanation differs essentially from that applied by PERRET to volcanoes with closed conduits, in which the maximum emission of gas is believed normally to take place at or near the beginning of an eruption [1]).

## Acknowledgement

Acknowledgement is made to the Director, H. M. Geological Survey, Gt. Britain, for permission to publish this paper. Pl. II, fig. 2, and Pl. III are crown copyright, and are reproduced from photographs supplied by the Director, the former by permission of the Controller, H. M. Stationery Office, London.

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1) PERRET F. A. « *The Vesuvius Eruption of 1906* », Carnegie Instit. of Washington, 1924, p. 59.


(*Photo* J. E. Richey)

View of Ben Hiant from the east.

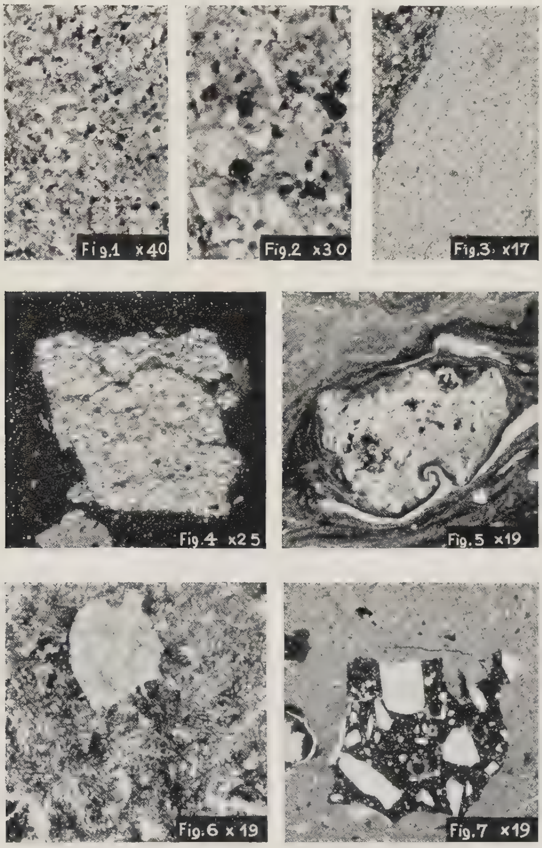
*m*, Moine Schists; *B*, Tertiary plateau Basalts; *V'*, Early Vent; *V''*, Later Vent; *qD*, Intrusion of quartz-dolerite, later than vents.

(*Photo* J. E. Richey)

Fig. 1. — Fine tuff overlain by agglomerate in the later vent of Ben Hiant, along base of cliffs north-east of Maclean's Nose.


 (*Photo* H. M. Geol. Surv., Scotl.)

Fig. 2. — Vertical margin of the later vent of Ben Hiant, marked by junction of vent-agglomerate with basalt lavas, along cliffs north-east of Maclean's Nose.




 (*Microphotos by* Geol. Surv., Lond.)

*Microphotos of Tuffs etc. Explanatory Notes.*

Fig. 1. — Fine dust-like tuff ( × 40 ). Locality : gully-section (top of 3, fig. 3, p. 10).

Fig. 2. — Somewhat fine sand-like tuff. ( × 30 ). Locality : base of cliffs N. E. of Maclean's Nose (see Pl. II, fig. 1). The clear shard-like grains are either quartz or plagioclase. The half-tone grains are mostly trachyte with incipient crystallizations. Darker patches are in part basaltic material. Black grains are iron-ore.

Fig. 3. — Part of trachyte fragment in tuff. ( × 17 ). Locality : gully-section (base of 3, Fig. 3, p. 10).

Fig. 4. — Fragment of Moine Schist in tuff. (× 25). Nicols crossed. Locality : gully-section (top of 1, Fig. 3, p. 10).

Fig. 5. — Fragment of basalt in rhyolite (the latter itself a fragment in tuff. (× 19). Locality : gully-section (at top of 4, Fig. 3, p. 10). Note : plasticity induced in basalt-fragment, marked by folded flow-line.

Fig. 6. — Variolitic basalt with altered olivine phenocryst, a fragment from a tuff. (× 19). Locality : gully-section (at top of 4, fig. 3, pag. 10). Note : felspar laths with fish-tail ends.

Fig. 7. — Felspar-phyric subvitreous basalt (ground-mass now opaque owing to development of iron-ore). A fragment in a tuff. (× 19). Locality : gully-section (at top of 4, Fig. 3, p. 10).

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# Crustal layers and the origin of magmas

*(With 4 text-figures)*

(Paper delivered at the Section of Volcanology, International Union of Geodesy and Geophysics, Sept. 22, 1936).

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## PART I.

### Petrological aspects of the problem.

By W. Q. Kennedy



## PART II.

### Geophysical data applied to the magma problem.

By E. M. Anderson

# PART I.

## Petrological aspects of the problem.

By

W. Q. Kennedy

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### Introduction.

During recent years it has become increasingly apparent that the problems of igneous activity are inseparably linked with those of geophysics on the one hand and crustal tectonics on the other. Any ultimate theory of petrogenesis must, therefore, seek to explain the origin of magmas and the evolution of igneous rocks both in terms of the physico-chemical processes involved and in relation to the major elements in the structure of the earth as a whole.

The first steps towards an understanding of this wider problem were made, more than thirty years ago, by Becke (Lit. 2) and Harker (Lit. 11, 12) when they pointed out that the characteristic igneous rock suites of the orogenic and non-orogenic areas are strongly contrasted in their chemical and mineralogical characters. Subsequent investigations, and more particularly those of Niggli (Lit. 15, 16) and the Zürich school (Lit. 6, 7), have served to confirm the fundamental truth of this generalisation, and tectonic environment is now recognised as an active factor in the evolution of petrographic provinces. At the same time, however, the actual mechanism of the tectonic control has not yet been adequately explained and it is with this latter aspect of modern petrology that we are mainly concerned in the present paper.

### The conception of volcanic and plutonic Associations.

Magmatic activity is expressed either in the subjacent intrusion of plutonic masses or by superficial volcanic ac-

tion and, before any comprehensive treatment of the subject can be undertaken, it is essential to understand the exact nature of the connection which exists between the two types of phenomena. The establishment of this important relationship is, indeed, the first step towards a rational theory of igneous evolution.

In the first place it must be emphasized that the intrusive or extrusive nature of many igneous bodies is an accidental character which has been determined largely by chance and as a result of local conditions. Any logical system of classification must recognise this significant fact and distinguish clearly between such « accidental » intrusions, which belong genetically to the volcanic group, and those in which the intrusive nature appears to be an inherent character. Current classifications fail utterly in this respect and we propose, therefore, to recognise two main groups of igneous bodies which may be termed *volcanic* and *plutonic associations* respectively. The former will include not only the superficial lava flows and vent intrusions but, in addition, all intrusive masses which are genetically related to a cycle of volcanic activity and originate in the same magmatic source. The plutonic associations, on the other hand, will comprise the great, subjacent stocks and batholiths together with the diverse minor intrusions of such abyssal masses.

*A Volcanic Association*, according to our conception, may include many intrusions which would, according to current views, be classed as plutonic or hypabyssal.

The great sill-swarms of the Karroo in South Africa and the Parana Basin of South America, for example, are of this nature and have been shown by Du Toit (Lit. 10) to be intimately and inseparably linked with the contemporaneous plateau basalt eruptions of the same areas. Similar relations, moreover, link the Palisade Sills and Watchung Basalts of New Jersey and, as both Du Toit (Lit. 10) and Backlund (Lit. 1) have pointed out, this intimate association of intrusion and extrusion must be regarded as characteristic of all plateau basalt areas.

Even the larger individual injected masses, such as the great Bushveld Igneous Complex of the Central Transvaal, may show typical effusive stages in their magmatic histories and belong unquestionably to a volcanic association, while, in the so-called « plutonic » centres of the British Tertiary Province, the evidences of simultaneous intrusion and explosive brecciation are obvious criteria of their essentially volcanic connection.

It is impossible to do more than mention a few typical examples which must serve to illustrate the point in question but it will be apparent to all petrologists that these few might readily be multiplied. Indeed, it can be stated as a generalization, that, almost without exception, the intrusive igneous bodies from non-orogenic areas, even when composed of rather typical plutonic rock-types, actually belong to a volcanic association, and their connection with an effusive episode can either be demonstrated, or at least, postulated by analogy with similar masses of proved volcanic affinity.

*Plutonic Associations* on the other hand appear to be limited to orogenic regions and include all subjacent masses (discordant and concordant batholiths, stocks, sheet complexes and related bodies) intruded within an orogenic belt during or immediately after an active orogeny, together with their associated aplitic, pegmatitic and lamprophyric minor intrusions. Many of the rock types possess no effusive equivalents nor has any true subjacent plutonic mass been found within a nonorogenic area. This latter feature alone is sufficient evidence of some fundamental genetical distinction between the rocks of the *volcanic* and *plutonic associations*.

If, now, the accepted view, which regards volcanic activity as a superficial expression of deep-seated plutonic intrusion and postulates an intimate connection between batholiths and surface volcanic centres, is correct, then certain grave difficulties at once become apparent. The first of these concerns the distribution and quantities of

igneous rock suites and the relevant data have been admirably summed up by DALY (Lit. 8) as follows :

« Among the visible intrusive rocks, the granites and granodiorites together have more than twenty times the total area of all other intrusives combined.

Among the extrusives, basalt probably has at least five times the total volume of all the other extrusives combined: basalt and pyroxene andesite together have at least fifty times the total volume of all other extrusives combined.

The granite and granodiorite clans, although dominant among the intrusives, are among the subordinate clans represented by the extrusives.

The gabbro clan is likewise subordinate among the intrusives but predominates among the extrusives.

The igneous rocks of the globe belong chiefly to two types: granite and basalt... To declare the meaning of the fact that one of these dominant types is intrusive and the other extrusive, is to go a long way towards outlining petrogenesis in general ».

DALY has contrasted volcanic and *intrusive* rocks but, as pointed out above, many of the latter actually belong to a *volcanic association* and are genetically connected with effusive episodes. If, on the other hand, we compare the rock types of *plutonic* and *volcanic associations*, the compositional differences indicated by DALY become even more pronounced.

It can be seen that the *plutonic associations* consist almost entirely of granodiorite and granite, together with smaller amounts of their associated, predominantly hornblendic, basic, ultrabasic and lamprophyric types, while typical gabbros are characteristically rare or absent. The *volcanic associations*, on the contrary, are overwhelmingly basic and are composed mainly of basaltic magma or of rock types belonging to a basaltic line of descent.

The acid rocks of the two associations, moreover, differ chemically as well as in their relative proportions. This feature has been pointed out recently by NIGGLI and LOMBARD (Lit. 17) who have contrasted 26 analyses af acid rocks from the Bushveld Complex (a typical intrusive member of the *volcanic associations*) with 47 analyses of similar

rocks from the Aar Massif and 15 from the Sierra Nevada batholith. In all cases the si-values exceed 300 and the distinctive natures of the two sets of intrusives are indicated by a statistical comparison of the mg-values.

| mg — value = | 0.0 — 0.1 | 0.1 — 0.2 | 0.2 — 0.3 | 0.3 — 0.4 | 0.4 — 0.5 |
|---|---|---|---|---|---|
| Bushveld Complex | 69 % | 23 % | 4 % | 4 % | — |
| Sierra Nevada . | 7 % | 0 % | 27 % | 33 % | 33 % |
| Aar Massif . . | 17 % | 13 % | 15 % | 38 % | 17 % |

We know that a granitic liquid can be produced by the fractional crystallization of basaltic magma and, within the volcanic associations, the relative proportion of acid to basic rock types and the chemical composition of the former is consistent with the view that the rhyolites, granophyres and granites of the non-orogenic suites have been formed by high-level differentiation and fractionation of a primary basaltic liquid. This mode of origin applies also to the *volcanic associations* of the orogenic zones where subordinate quantities of acid lavas are associated with the predominantly basic extrusives.

The acid rocks of the true *plutonic associations*, however, represent such an enormous bulk of granitic and granodioritic material that it is impossible to conceive of their derivation from a basaltic parent and we are forced to conclude that they must have formed from some primary acid magma such as the granodioritic parent melt postulated by Wahl (Lit. 20). It is important, in this respect, to remember that Daly originally based his conception of the parental status of basaltic magma on the supposed fact of its occurrence as the only constant member of all rock associations. While this is unquestionably true of the volcanic associations it does not hold in the case of the true plutonic complexes from the orogenic zones, in which as a rule gabbroic rock types are rather con-

spicuously absent. Some modification of current theory is obviously necessary and it is suggested, therefore, that basaltic magma represents the universal parent of the volcanic associations and that the plutonic associations originate in a primary acid granodioritic melt.

A further point of difference between the two main classes of magmatic phenomena depends on the presence or absence of inclusions. Plutonic masses are characterised by the abundance of inclusions, both cognate and accidental, which they contain, and these are often present in sufficient quantities to constitute an appreciable proportion of the total mass. Associated effusive rocks, on the other hand, are characteristically devoid of inclusions in any way resembling those of the plutonics. If lava flows are indeed the effusive outpourings of subterranean batholiths, both should contain identical inclusions unless, as seems improbable, the latter are completely resorbed during extrusion. The fact that such inclusions are absent is again suggestive of the lack of intimate connection between the plutonic and volcanic associations.

This conclusion appears to find support also in the observed relations of batholiths to their roofs, and Bucher (Lit. 5) in particular has emphasized the fact that the large acid plutonic masses of the orogenic belts are capable of penetrating the crust to points very near the surface without bursting their roofs in catastrophic fashion. Under such circumstances, moreover, they do not appear to give rise to surface eruptions but actually cut the effusive rocks of the same igneous episode. This universal absence of lavas belonging to a period contemporaneous with the rise of batholithic intrusions to their highest levels in the crust is of considerable importance. It suggests that, if the volcanic rocks of the orogenic zones are the effusive equivalents of the plutonics, then it is necessary to postulate that a batholith is capable of establishing a communication with the surface *before* it has advanced into the higher levels, but that when it has penetrated to within a short distance of the surface such volcanic outbursts are

no longer possible. This is definitely at variance with our knowledge of magmas and it is probable that the same factors which control the intrusion level of plutonic masses would also effectively prevent them from establishing parasitic volcanic centres. It is possible that certain of the great rhyolitic floods may have been produced by areal eruptions due to the collapse of a batholithic roof as DALY has advocated, but this must be of very exceptional occurrence in view of the relative paucity of acid volcanic rock. Altogether, there does not appear to be any very direct evidence to indicate a close connection between plutonic activity and volcanicity.

One further line of evidence sheds some light on this problem and may be considered briefly. It concerns the various theories which have been advanced from time to time in order to explain the origin of igneous rocks. These belong, in general, to two main categories : the contamination school believe that it is necessary to postulate widespread assimilation and contamination of the magma in order to explain the diversity of igneous rock types and igneous rock series. The other school, of which N. L. BOWEN is the great exponent, bases its conclusions on the concrete evidence of experimental investigation and ascribes the diversity of igneous rocks to processes of fractional crystallization operating on an uncontaminated parent melt. This latter view naturally admits the possibility of assimilation but regards such processes as of secondary importance in petrogenesis.

An analysis of the methods of these two schools of thought reveals the interesting and significant fact that, whereas the advocates of widespread assimilation base their views on evidence derived predominantly from *plutonic associations*, the exponents of fractional crystallization have been concerned mainly with volcanic provinces. The theory of fractional crystallization does undoubtedly explain many of the major and minor features of volcanic rock suites, but it encounters grave difficulties when applied to the subjacent plutonic complexes of the orogenic zones. Similarly,

the *plutonic associations* reveal marked evidence of contamination, as NIGGLI and LOMBARD (Lit. 17) have pointed out, but assimilation will not explain the observed sequences of volcanic rocks.

Such a divergence of views can readily be explained if, as we believe, the *volcanic associations*, on the one hand, and the *plutonic associations*, on the other, result from different causes and have originated by different processes. It is obvious that any attempt to explain plutonic complexes in terms of evidence derived from the study of volcanic processes will, under such circumstances, lead only to confusion, and it is highly probable that the chaotic condition of modern petrogenetical thought results, in no small measure, from the failure of petrologists to distinguish clearly between the intrusive membeıs of the two igneous associations.

The various lines of evidence which have been considered briefly above are, individually, of no very great significance. Collectively, however, they do appear to point to certain general conclusions which are, at least, worthy of some consideration. These conclusions may be summed up as follows :

*a) Volcanic* and *plutonic associations* represent two distinct and apparently independent expressions of magmatic activity: they have their origins in different parent magmas and their subsequent evolution is controlled by different processes.

*b) Volcanic associations* are derived from a universal basaltic magma (or magmas) which originates by remelting of a basaltic earth shell, the intermediate layer.

*c) Plutonic associations*, despite their more deep-seated location, originate at a higher level and are derived from a primary, universal, granodioritic parent magma. The latter develops by remelting of the so-called « granitic layer ». Such remelting would only be possible within the orogenic zones of the earth where tectonic thickening of the crust brings the base of the granite layer within the range of melting.

*d)* The actual mode of irruption differs in the two cases. The granite and granodiorite batholiths appear to penetrate slowly upwards, accompanied by a wave of granitization and migmatitization of the

country rocks, until arrested by some unknown form of hydrostatic control before they reach the surface. The ascent of basaltic magma is entirely different, no vast intercrustal reservoirs are formed, and the basaltic melt appears to be irrupted directly towards the surface through a system of relatively narrow, dykelike fissures. It is then either extruded in the form of lava flows or else gives rise to larger or smaller injected bodies, such as sills and laccolites, which may themselves represent volcanic reservoirs. Differentiation of the basic magma, moreover, takes place within the levels of crystallization and, in consequence, the magmatic evolution is controlled largely by fractional crystallization.

It is obvious from the foregoing that, as true plutonic rocks occur only within the orogenic belts and are inevitably connected genetically with crustal movements of orogenic type, they can be excluded from a discussion of the tectonic relations of the alkaline and calc-alkaline rock suites. This problem concerns only the volcanic associations and is dealt with below.

There remains, however, one general theory of the igneous rocks which must be referred to, namely, the conception of an ultrabasic parent magma. This was advocated originally by Holmes (Lit. 13) and has been extended in recent years by Reynolds (Lit. 18) who seeks to explain the origin of igneous rocks, and more particularly those of the plutonic associations, on the basis of a supposed interaction between primary ultrabasic magma, on the one hand, and the sedimentary rocks of the earth's crust, on the other. Quite apart from the known reluctance of ultrabasic rocks to engage in processes of assimilation within the visible levels of observation, however, it may be stated that the formation of a primary ultrabasic magma by remelting of the earth's peridotite shell is highly improbable in view of the physical restrictions. Bowen and Schairer (Lit. 3) have recently investigated the nature of the olivine diagram and their results, taken in conjunction with the geophysical considerations discussed in the second part of this paper, seem to indicate that no appreciable quantity of primary ultrabasic magma would form within fifty kilometres of the surface. This is in ac-

cordance with the widely held view that the ultrabasic rocks are crystalline derivatives of some less basic magma and have not crystallized from liquids of their own composition.

It is also worthy of note that any magmatic process which originates at a depth of more than fifty kilometres must be more or less independent of crustal tectonics. If we invoke the processes postulated by Reynolds, then it becomes a matter of almost insuperable difficulty to explain the restriction of plutonic rocks to the orogenic zones. The fact that igneous rocks in general do exhibit a direct relationship to surface tectonic processes affords good evidence that they must originate at relatively shallow depths and well within the sphere of influence of superficial crustal movements.

## The rôle of tectonic environment in the evolution of the volcanic associations.

Certain of the more general aspects of magmatic activity have been outlined in the preceding section and the remainder of the paper will be devoted to a consideration of the relationships exhibited by *volcanic associations*. The latter include two main lines of descent, the alkaline and calc-alkaline series, and one of the chief problems of petrogenesis is to explain the origin and tectonic associations of these natural igneous rock suites.

Basaltic magma is the only member common to both series, and among all the diversity of volcanic rocks it is possible to recognise two predominant magmatic sequences, the basalt-andesite-rhyolite series and the basalt-trachyandesite-trachyte series. The former is characteristic of the calc-alkaline suite, the latter of the alkaline division, and between them they include all but a relatively insignificant proportion of the total volume of rocks belonging to the volcanic associations [1]).

1) It must be pointed out, however, that this insignificant proportion includes the extreme alkaline types which, although present in

The salient features of the distribution and tectonic relationsphips of these contrasted lines of descent may be summed up as follows :

a) *Volcanicity within the orogenic belts leads to the development of the basalt-andesite-rhyolite (calc-alkaline) line of descent, whereas contemporaneous volcanicity within the non-orogenic areas, and even in the immediate foreland and hinterland of the movements, is characterised by the basalt-trachyandesite-trachyte (alkaline) series.*

This general relationship is well known and requires little further comment. It is expressed by the occurrence of calc-alkaline lavas throughout the Circum-Pacific orogenic zone and by the development of alkaline types within the Pacific basin itself and in the foreland provinces (Montana, Yellowstone, etc.).

Volcanicity is much less general throughout the Alpine-Himalayan belt but there also alkaline rocks are developed in the foreland (Auvergne, Eifel, Hagau, etc.) whereas strongly calc-alkaline types are found within the folded zone as in the Carpathians.

very small quantities, nevertheless are of great petrogenetical significance. Such extreme alkaline types are always associated with normal members of the basalt-trachyandesite-trachyte series and, whatever their true origin may be, it is obvious that it must be controlled in the first place by the development of a magma belonging to the normal alkaline line of descent. Thus, Rittmann has recently discussed the evolution of the Vesuvius magma and has advanced very strong arguments in favour of assimilation. It is important, however, that his scheme of evolution involves the contamination of a *trachytic magma* and the first step towards a complete interpretation of the magmatic sequence must be to explain the origin of the orignal alkaline trachyte.

Each stage in the evolution of the basalt-trachyandesite-trachyte series represents a possible starting point for subsidiary lines of descent leading to more extreme types. It is not the purpose of this paper to discuss the detailed evolution of the alkaline rocks, and the possibility of limestone assimilation and other processes does not concern us. We do know, on the other hand, that extreme alkaline igneous rocks are associates of the main basalt-trachyandesite-trachyte sequence and we believe rightly or wrongly, that a discussion of the origin and tectonic relationships of this central series will go far towards a solution of the problems concerning the alkaline rocks in general.

Exceptions to this general rule do occur and must be accounted for by any logical theory of magmatic evolution.

b) *Any region may, at one period in its geological history, represent an alkaline province while, at some other period, it may equally well form a typical calc-alkaline province.*

This condition is well illustrated by the Midland Valley of Scotland where the typically calc-alkaline basalt-andesite-rhyolite association of the Lower Old Red Sandstone volcanic episode forms a striking contrast to alkaline basalt-trachyandesite-trachyte line of descent which characterises the Carboniferous volcanicity of the region. The significance depends on the fact that, during Lower Old Red Sandstone times the Midland Valley lay within the main Caledonian orogenic belt whereas, during the Carboniferous it formed part of the Hercynian foreland.

« Temporal » variations of this kind are of great petrogenetical importance although they tend to be overlooked on account of the more obvious « lateral » variations. As a general rule, however, it is found that, in any region which has been the scene of recurring periods of volcanic activity, the development of a calc-alkaline suite is followed during later igneous episodes by alkaline rock suites.

c) *Within certain regions the two contrasted lines of descent are intimately associated in space and time.*

The British Tertiary Province and Madagascar afford good examples of such mixed provinces and, within these regions, it is clear that typical alkaline and calc-alkaline magmas must have been simultaneously available throughout the eruptive histories of the centres.

In attempting to explain these wider relationships between magmas and tectonic movements, we may commence with Daly's conception of the primary basaltic parent magma.

Primary basalt magma must possess certain essential characters. It must represent a true liquid and, in addition,

show world-wide distribution in space and time, uniformity of composition and great aggregate bulk. These characters, however, are fulfilled by two types of basaltic material, the olivine-rich basalts and dolerites and the olivine-poor and olivine-free basalts, dolerites and quartz-dolorites (Lit. 14). This has led the writer (Lit. 14) to postutate the existence of two primary basaltic magmas, the *Olivine-Basalt Magma-Type* and the *Tholeiitic Magma-Type*, and to explain the origin of volcanic rocks on the basis of the contrasted differentiation of these parental melts.

The chief characters of the two types are summed up below and are discussed at length in the original paper.

**Chemical Composition.**

| | Olivine-Basalt Magma-Type | Tholeiitic Magma-Type |
|---|---|---|
| $SiO_2$ | 45 | 50 |
| $Al_2O_3$ | 15 | 13 |
| $Fe_2O_3$ + $FeO$ | 13 | 13 |
| $MgO$ | 8 | 5 |
| $CaO$ | 9 | 10 |
| $Na_2O$ | 2.5 | 2.8 |
| $K_2O$ | 0.5 | 1.2 |

*Olivine-Basalt Magma-Type.* The essential minerals are olivine, augite, basic plagioclase and iron ore. The pyroxene is a lime-rich diopsidic augite or titanaugite. A little residual, interstitial material is often present and this is of alkaline nature (analcite, etc.), without free quartz.

Rocks belonging to this magma-type are of widespread occurrence and are known from all the Geological Systems. They occur as plateau lavas, particularly in the Thulean province, and form extensive lava-fields around many of the great shield volcanoes. This is also the common basalt of the oceanic volcanoes.

*Tholeiitic Magma-Type.* The essential minerals are pyroxene, basic plagioclase and iron ore. Olivine is either

completely absent or else present in very subordinate amount. The pyroxene is either a lime-poor pigeonite or else a mixture of orthorhombic and monoclinic pyroxene may be found. Characteristically an interstitial, acid residuum is developed which may be glassy or else of quartzo-feldspathic composition. Quartz is often developed in the later stages of crystallization.

Basalts and dolerites belonging to this magma-type are widely distributed. The majority of the so-called plateau basalts are of this type, to which belong also the quartz-dolerites of the great Karroo and Parana sill swarms. It is probable that many of the andesites of the Cordilleras are actually olivine-free basalts of the tholeiitic magma.

Evidence regarding the petrogenetic affinities of these two magma-types was obtained from a study of their regional associations and late differentiates. It was found that the segregation veins or pegmatitoides of the olivine-basalt magma-type were of alkaline nature whereas those of the tholeiitic magma-type were strongly calc-alkaline. A regional study of the distribution of the rocks confirmed the association of olivine-basalts with alkaline provinces and of tholeiitic magmas with rock suites of calc-alkaline type. The general thesis was therefore advanced that *the olivine-basalt magma-type represents the parent of the alkaline rocks and the tholeiitic magma-type that of the calc-alkaline series*. The general scheme of magmatic descent is as follows :

| **Alkaline** | **Calc-Alkaline** |
|---|---|
| Olivine-Basalt Magma-Type | Tholeiitic Magma-Type |
| ↓ | ↓ |
| Trachyandesite | Andesite |
| ↓ | ↓ |
| Trachyte | Rhyolite |
| ↓ | |
| Phonolite | |

Recent investigations in various parts of the world would appear to confirm the essential correctness of the theory (Lit. 4,19), which at least provides a useful basis for further investigation, and certain additional lines of study have become apparent. In particular, the conception of the two basaltic lines of descent provides a clue to the vexed question of the tectonic relationships of the alkaline and calc-alkaline suites.

In the original paper (Lit. 14) it was pointed out that, whereas the olivine-basalt magma appears both in the continental areas and in the oceanic basins, the tholeiitic magma is consistently absent from the latter and appears to be connected with the presence of the granitic crust.

The original conception of a basaltic layer underlying the granitic crust of the earth was based on the enormous bulk and uniform composition of the basaltic rocks visible at the surface of the globe. The existence of such a basaltic layer, moreover, would appear to be essential to any theory of igneous activity.

At the same time the enormous bulk and uniform composition of each of the two parental basaltic magmas leads us to postulate the existence of two basaltic layers underlying the granitic crust. We believe that the granitic shell is succeeded in depth by a shell of tholeiitic composition and that, in turn, by an olivine-basalt layer. Below the oceanic regions, however, both the granitic and tholeiitic shells may be absent. The ultimate origin of the tholeiitic shell, whether it results from contamination of an original olivine-basalt magma by the granitic shell or not, is immaterial from the point of view of the present paper.

If we are correct in assuming such an arrangement of the outer shells of the earth, and there is some supporting evidence to be derived from a study of earthquake waves (p. 22), then it becomes possible to advance a theory which will account for the tectonic associations of the alkaline and calc-alkaline rock-suites. Thus, during the development of a major orogeny, the granitic crust will be-

come thickened and bent downward (Fig. 1). This downwarping will probably affect the underlying basaltic shells as well.

With the consequent rise of the geoisotherms a tendency towards melting will be set up within the basaltic shells underlying the orogenic belt and the tholeiitic shell will melt and give rise to a liquid of tholeiitic composition.

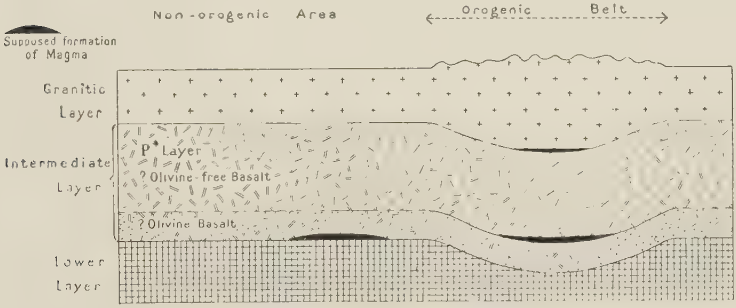


Fig. 1. — Supposed Sources of magmas, in orogenic and non-orogenic areas.

On eruption this tholeiitic basaltic magma will differentiate and produce a basalt-andesite-rhyolite series.

The conditions below the foreland or hinterland sectors, and throughout the non-orogenic areas as a whole, would, however, be entirely different owing to the fact that both the basaltic shells would there lie at a higher level than in the case of the orogenic zones. The upper limit of melting would, therefore, lie below the tholeiitic layer and only olivine-basalt magma would be produced. On eruption this olivine-basalt magma would differentiate with the production of alkaline rock types belonging to the basalt-trachyandesite-trachyte line of descent.

Members of the basalt-andesite-rhyolite association are absent from such non-orogenic areas for the same reason that granodiorite batholiths are absent (p. 31), namely because melting of the primary earth shell was not possible with the heat available.

In some cases, however, as during plateau basalt eruptions, regional melting appears to have taken place on an enormous scale and both olivine-basalt and tholeiitic magma have been produced simultaneously. Each parent magma will differentiate according to a predestined plan and the region will be characterised by an intimate mixture of alkaline and calc-alkaline differentiates.

In conclusion it may be pointed out that the above discussion is purely of an exploratory nature and many discrepancies are inevitable. At the same time we consider that the views are worth advancing as they do explain certain of the puzzling relations exhibited by magmas and it is hoped that they may afford some clue to possible further lines of investigation.

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# PART II.

## Geophysical data applied to the magma problem.

By

E. M. Anderson

In this section attention will be paid in particular to recent work in seismology, but data of many kinds will be used, as every other branch of geological physics has some bearing on the magma problem. The enquiry will lead to certain suggestions on the origin of volcanic activity as a whole, which, it is thought, are themselves worthy of discussion.

For the purpose of our enquiry it is necessary, in the first place, to consider the question of crustal temperatures. In regard to these there are two wery discordant « schools ». One of these was represented by the late Professor Joly, who held that temperatures not far below those of fusion occurred at a certain depth throughout the whole of the continental crust, and had only to be slightly augmented to produce melting, with consequent vulcanicity. In distinction to this « school » is that which regards mountain formation as due to earth contraction, caused by cooling. It is a necessary part of this hypothesis to suppose that temperatures down to great dephts are, fairly uniformly, several hundreds of degrees below the corresponding points of fusion. How, under these circumstances, vulcanicity can arise, has never, we think, been made very clear, but attention may be directed to certain hypotheses which have been put forward by petrologists.

According to one of these melting takes place in certain cases owing to relief of pressure. This theory has not,

however, been given the necessary quantitative discussion. At a depth of, say, 20 kilometres it is impossible to suppose that the *vertical* pressure can be reduced, over any large area, by more than a small fraction of its own amount. A greater reduction of pressure, at such a depth, could only be due to the fact that the layers above were functioning as an arch. This in its turn would imply an impossible increase of horizontal pressure. Even if the whole superincumbent weight were removed at the depth mentioned, the temperature of fusion would only be lowered by about 60°. A small fraction of such a removal of pressure would therefore not be effective. Melting on a large scale is not due to a vertical relief of pressure, and must be caused by a lateral variation, if the element of pressure is to be invoked at all.

A unilateral decrease of pressure at a given depth may quite possibly lower the corresponding fusion point. There is no direct evidence that it does so, but it seems theoretically probable. According to JOHNSTON and ADAMS, either a small reduction or a small increase of lateral pressure, in relation to the vertical, may cause a lowering of the fusion point of a rock body, of comparatively large amount (23). Judging from their data, however, the first consequence will not be the production of a large body of magma, but of a condition of deformability in the rock. In this way the vertical and horizontal pressures will be equalized, and if the inequality can arise at all near melting temperature, it will only be temporary. These authors' very interesting suggestion is at present only hypothetical, and in any case it can hardly be made to support the Contraction Theory. It is easier to believe that a horizontal reduction or increase of pressure may lower the effective melting point by say 20° or 30°, but even this is so far unproved.

It might be argued however that a rock mass which was much below its average temperature of melting might contain pockets or layers of more readily fusible rock. These might contain a larger proportion of volatile constituents.

Such a theory might account for intrusive activity, but hardly for the facts of vulcanicity. Lava comes to the surface at temperatures high enough to melt the residuum after any such excess of fluxes has been removed. It seems to be impossible to reconcile the divergent view-points by any hypothesis of this sort.

For these reasons the authors believe that JOLY's theory is the correct one, and that crustal temperatures at a certain depth, or depths, are never very far below the points of fusion. In the course of the enquiry it will be shown that certain difficulties, which formerly prevented the ready acceptance of the theory, have been to some extent removed.

## Seismological Data.

One may next consider the bearing on the magma problem of what has been perhaps the most important advance in recent seismology. This was the recognition, in continental areas, of two double systems of waves, the $P_g$ and $S_g$ system, and the $P^*$ and $S^*$ system, which must have travelled along higher levels of the crust than the previously known $P_n$ and $S_n$. It is certain that each system is characteristic of a definite layer, which may not, however, be of uniform thickness. The $P_g$ layer must overlie the $P^*$ layer, and that again the much thicker layer, or earth-shell which gives rise to $P_n$ and $S_n$.

The different waves in the two higher layers have a more or less constant velocity. They can be followed for long distances, and are found to spread from widely separated earthquake centres, although more is known about them at present in Europe than in most of the other continents. From these facts alone it is fair to argue that there must be a certain amount of lateral uniformity in the continental crust.

In the vertical direction seismology has confirmed what on other grounds had already been inferred, namely that the crust is not homogenous. It has however shown a fact which might not have been suspected : — that the vertical

variation is not continuous. Within the thicknesses of the $P_g$ and $P^*$ layers there must be a certain amount of uniformity, and these thicknesses must be considerable. The underlying $P$ or $P_n$ layer must also be fairly uniform, to a depth, it has been recently advocated, of about 480 kilometres. The major changes must occur between these layers, and must therefore be relatively abrupt.

The layer which conducts the $P_g$ and $S_g$ waves has been identified with the previously inferred granitic layer. One of us has elsewhere suggested that it may be similar in character to, and represented at the surface by, the Scottish Lewisian Gneiss, and thus in bulk composition more basic than granite (3). The wave velocities show, however that it can only be to a moderate degree more basic. Its thickness, outside the orogenic belts, has usually been estimated at from 10 to 13 kilometres.

An interval of less than 25 kilometres probably separates the base of the granitic layer from the top of the « lower layer » which gives rise to $P_n$ and $S_n$. The name « intermediate layer » has been applied to the whole of this thickness. A moderately large part of it must be constituted by the layer of $P^*$ and $S^*$. It has however been suggested by various seismologists that this fraction is not the whole. Waves have, it is claimed, been discovered, which are intermediate in velocity between $P^*$ and $P_n$, and indicate determinate layers underlying the $P^*$ and $S^*$ level, but overlying that of $P_n$ and $S_n$. Thicknesses have even been calculated for these layers, but the different results are not yet consistent, and Dr Jeffreys has informed the authors that he considers any such subdivision of the intermediate layer as being still open to doubt.

The subdivision would, if it could be proved, be of some importance to petrography. The reason of its significance lies in the difficulty which at present exists in explaining the provenance of basalt. In the words of Prof. Holmes « The prevalence of basaltic rocks throughout geological time requires that we cannot lightly give up the basaltic layer ». But the $P^*$ and $S^*$ waves indicate con-

stants, such as $k$ the bulk modulus, which are too small to agree with most determinations of the moduli for basalt, or with those for gabbro. For this reason it has been suggested that the layer may consist of diorite, and JEFFREYS has supposed that it may be tachylyte. The « lower layer » on the other hand has constants which are higher than those of basalt or gabbro ; it may be dunite, or peridotite, or possibly eclogite.

The number of determinations of the elastic constants of basaltic rocks, and of gabbro, which have yet been made at the appropriate pressures, is, however, not very large. In the first part of this paper the importance of the subdivision of this group of rocks, into olivine basalt and gabbro on the one hand, and quartz-bearing basalt and its equivalents on the other, has been emphasized. This subdivision has not yet been taken into account by experimentalists in tabulating their results.

BIRCH and DOW have measured the bulk modulus of olivine basalt from Vinal Creek, through a wide range of pressures, at ordinary temperatures, and also at 376° and 416° (5). They found that, on the whole, the rock was more compressible at the higher temperatures. The effect was, however, very irregular We have used the results obtained for unheated basalt by BRIDGMAN, ADAMS and WILLIAMSON, and ADAMS and GIBSON (7, 1, 2) selecting only those experiments in wich the rock was not enclosed in a thin metal casing. The discussion of the subject by ZISMAN (34), among other things, probably shows that this is right. The experiments have shown that compressibility decreases with pressure, and therefore with depth. The velocity of the longitudinal wave which should correspond to a compressibility $\beta$ is given by the formula

$$U_p = \sqrt{\frac{3\,(1-\sigma)}{\beta\rho\,(1+\sigma)}}$$

where $\sigma$ is POISSON's ratio, and $\rho$ the density. It must be remembered not only that $\rho$ varies with pressure, but also

that this variation affects the strict value of $\beta$. We have assumed that $\sigma = \cdot 25$. If $\sigma = \cdot 27$, as is often supposed in such calculations, the velocities arrived at will be about 2 per cent smaller.

By applying the formula to the values of $\beta$ which are inferred for a pressure of 5,500 bars, corresponding to a depth of about 20 kilometres, we have calculated the longitudinal velocities which are shown in the diagram (Fig. (2).

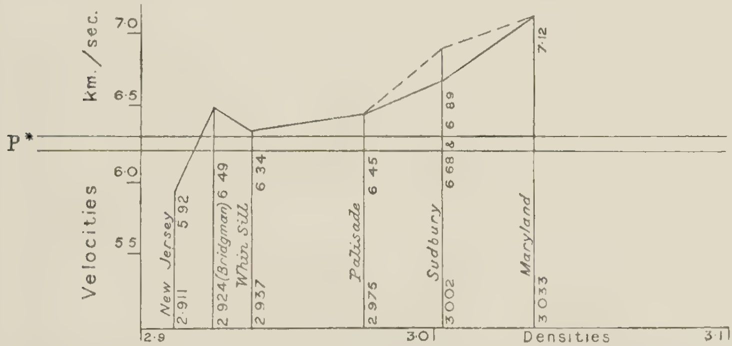


Fig. 2. — Longitudinal wave-velocities, as related to densities, in basaltic rock.

In this the horizontal ordinate is the surface density. It will be seen that the speeds on the right hand of the figure, corresponding to densities of 3 or over, range up to 7 kilometres per second. Those on the left, for rocks with densities nearer to 2·9, average 6·2 or 6·3.

Analyses of the rocks, and details of the modes are given by most of the authors, and are sufficient to show that in a broad way the right hand and left hand values correspond respectively to the two classes of basaltic rock. The three on the right correspond to rocks containing no quartz, either in the norm or mode. In one case (Palisade diabase), olivine occurs in the norm, and in another case (Sudbury diabase), both in the norm and mode. The two lowest velocities are for rocks containing quartz in the norm or mode.

The velocity of the $P^*$ waves has been taken to be 6·2 or 6·3 km./sec., and two lines have been ruled in the diagram, corresponding to these two values. The difficulty of finding a basaltic layer by seismological methods will be seen to be overcome, if the methods of calculation are correct, and the term basalt is used to include the tholeiitic basalts. The Whin Sill rock of Northumberland is a typical member of this class. The corresponding $U_r$ is found to be 6·34, and if one remembers that earthquake velocities may well be reduced a little by high temperatures which are not allowed for in the calculations, the correspondence is particularly good.

It is therefore suggested that the horizon which conducts the $P^*$ and $S^*$ waves, and constitutes at least the upper part of the « intermediate layer », consists of tholeiitic basalt or the equivalent type of gabbro, in the crystalline state. An « Upper Intermediate Layer » providing « a potential source for olivine-free basalt rocks » has already been advocated by Holmes, but he supposed the material of the layer to be in the amphibolite facies (18).

It is to be regretted that none of the specimens on which experiments have been made appears to be an absolutely typical olivine basalt. One of them (Sudbury) contains 15 per cent of olivine, but is too low in magnesia. The rock which Bridgman tested contains 10 per cent of olivine, but the presence of glass, as well as the low specific gravity, indicates an affinity with the tholeiites. The Maryland diabase does not contain olivine, at least in the calculated mode, but it is high in magnesia. If one averages its velocity with the one derived from the later and better determinations of the bulk moduli for Sudbury, one obtains the value 6·9 km./sec. It is to te be noted that various seismologists have concluded that there is a layer characterized by nearly this longitudinal velocity. Thus Gutenberg inferred that there is a layer corresponding to a speed of 6·83 km./sec. in California (16). Stoneley detected a wave with velocity 7 km./sec. (32), and on the strenght of this Lee inferred that there is a « Lower In-

termediate layer », as well as an « Upper Intermediate », or $P^*$ layer, in Europe (26). More recently Sparks has argued for the existence of a thick layer with velocity 7 km./sec. in California (31). It thus seems at least possible that there is a distinct layer of crystalline material of like composition to olivine basalt, underlying the tholeiitic layer which we advocate. An olivine basalt layer at this level has in fact been suggested by Holmes (18).

The petrological evidence should be taken into account, along with the seismological evidence, and it might be considered enough in itself to prove the point. But the seismological evidence is not at present consistent. Thus Sparks' vertical section of the crust does not include a $P^*$ layer, though Gutenberg had previously identified a layer with nearly the appropriate velocity, likewise in California. It will be well, we think, to wait for further data, and to leave the question open. A good case for the tholeiitic basalt layer can certainly be made out. An olivine basalt layer may be inferred for a different reason. The seismological evidence available perhaps also suggests this inference, but it does not amount to proof.

## Thermal Relations in an Unthickened Crust.

We wish next to consider the bearing of these more or less probable speculations on the question of igneous activity. The method of investigation proposed is to draw two curves, representing as nearly as present information permits (1) the actual temperature within the crust, as a function of depth, and (2) the temperature at which fusion would be sufficiently complete to allow vulcanicity. In tracing the latter curve it will be assumed that the melting point is not affected by any difference of the lateral from the vertical pressure. Both curves will be drawn, in the first place, for an area where there has not been recent orogenesis. The two will then be compared, to see at what point or points they meet, or if they do not meet, are in mearest proximity.

Dealing first with the fusion curve, it will be appropriate to regard it not as a single line, but as a band of more or iess indefinite width. This is more particularly the case for the granitic portion of the crust, as shown by the experiments of Greig, Shepherd, and Merwin (15). They found that, in granite, some melting probably occurs at 570°, and certainly at 700°, while in one week the powdered rock becomes half liquid at 800°. As there is no restriction in time, one is probably justified in beginning the fusion curve, at the top of the granitic layer, at a temperature of about 700°.

In sketching the curve we have been forced to make certain assumptions about the thicknesses of layers, etc., but these are of course purely tentative. The granitic layer has been taken to be 11 km. thick, the $P^*$ layer to consist of quartz basalt or gabbro 18 km. in depth, and to overlie 6 km. of olivine basalt. The « lower layer » has thus been supposed to begin at 35 km., while the sedimentary layer, which usually overlies the granitic layer, may for our purpose be neglected. It has been assumed that the fusion points of the materials of the different layers rise uniformly, owing to increase of pressure, at 3° for every kilometre of depth. The base of the granitic layer has thus been given a melting point of about 733°.

The melting point of basalt has not perhaps been investigated in so thorough a manner as was done by the authors quoted in the case of granite. They state however that corresponding degrees of fusion would occur at temperatures about 300° higher. This probably refers in the main to olivine basalt, and it may therefore be assumed that at zero pressure this type would melt at about 1000°. With regard to tholeiitic basalt the data are even less definite. Douglas found that quartz diabase melts at 1085-1105°, and the rock of the Whin Sill at 1107° (10). The same process however gave a fusion point of 1235-1255° for Shap granite, and 1215° for Peterhead granite. The criterion of melting applied must therefore have been quite different from that of Greig, Shepherd, and Merwin. It

seems theoretically probable that quartz basalt will melt at a lower temperature than olivine basalt. Olivine itself has a high fusion point, but this consideration does not count for so much as the difference in the types of felspar. When it is remembered that the melting point of anorthite is given as 1550°, and of albite as 1100°, it is not unreasonable to suppose that the difference of that of the two rocks may be as much as 50°. It has therefore been assumed that the surface melting point of quartz basalt is 950°, though of all the data used for the present curve this most needs confirmation. If the material, which underlies the supposed layer of olivine basalt is dunite, or peridotite, it has certainly a much higher melting-point. If the layer consists of dunite, that is of olivine, it seems improbable, from considerations of specific gravity, that its composition can be very different from that of the type of olivine most usual in surface rocks, into which the fayalite molecule only enters to the extent of 10 or 15 per cent. For this type Bowen and Schairer have found that the point of complete melting lies about 1850° (6). Their diagram indicates, however, that melting might begin about 1700°. If the layer consists of peridotite, as we shall assume for the meantime, the fusion-point will be lower, but in view of Bowen and Schairer's results, we think we are justified in taking the figure for zero pressure as high as approximately 1500°. We do not know of any data for eclogite, but this type also may have a much higher melting-point than basaltic rock.

With these admittedly rather indeterminate data the tracing of the fusion curve has been attempted. At about 11 km. in depth the curve or band must rise more or less abruptly from about 733° to about 983°. It must then continue with only a gentle gradient to a depth which we are assuming to be 29 km. At this point it again rises suddenly from 1037° to 1087°, according to our assumption. If this is true it involves a further gentle gradient extending to 35 km., where there is a third more or less sudden rise, from 1105° to 1605°.

Though the curve is in some ways theoretical, other features may be regarded as certain. The breaks which have been drawn at 11 km. and at 35 km. must, whatever be their actual depths, be real. It is uncertain, however, to what extent they are abrupt. This depends on the sharpness, or gradualness, of the transitions, and as far as we know this point has not yet been decided by seismologists. The flat reaches corresponding to the granitic layer, the $P^*$ layer, and the « peridotite » layer must also be realities. The break at 29 km., and the gentle gradient beneath it are both less certain, but they may be accepted for the sake of argument. The actual curve may not, in many ways, be the same as what has been represented. But it cannot in any case be smooth ; there must be at least two downward bulges, with more or less projecting points.

One has next to consider the distribution of temperature. As already mentioned. certain recent developments have discounted the main objection which could formerly be urged against the acceptance of JOLY's theory. The difficulty mainly arose from the low rate of transfusion or flow of heat at the surface, which was inconsistent with the supposed high constant of radioactive production of heat in the granitic layer. With a constant as large as was formerly supposed the gradient of temperature at the base of the layer had to be much less than that at the surface. The temperatures of the two supposed basaltic layers could not then have approached those of fusion. As was shown by one of us (3), a lower constant can probably be inferred on the assumption that the granitic layer appears at the surface in the form of the Scottish Lewisian Gneiss. Since then the matter has been placed on a firmer footing by the statistical study of the constants of various classes of granite which has been made by JEFFREYS (22). He concludes that « it is precisely those granites which have not been formed from the granitic layer that have the best chance of resembling this layer, and the Scottish and North American means will be the best for our purpose ». These

two groups form part of a class with a small content both of radium and thorium; for the class as a whole the values $Ra = 1.59 \times 10^{-12}$ and $Th = 0.81 \times 10^{-5}$ are given as an average.

A factor which has an important bearing on the radioactive constants to be assigned to crustal rocks, and to granite in particular, is the figure which is adopted for the heat generation of potassium. With regard to this it is to be noted that HOLMES has now reduced to about one sixth the figure originally put forward by himself and LAWSON (17, 19). If one adopts the proportions given above for radium and thorium, and uses the reduced value of HOLMES' constant, while supposing that the percentage of metallic potassium in granite is 3·4, one obtains for the rock a heat generation of only $1 \cdot 88 \times 10^{-13}$ cal./gm.sec., or $5 \times 10^{-13}$ cal./cm.$^3$ sec. Quantities of the dimensions of the last may be denoted by A, and A for granite was at one stage supposed by JEFFREYS to be over twice as much. Using the new potassium constant, the estimated value of A for the Lewisian Gneiss is about $6 \times 10^{-13}$ cal./cm.$^3$ sec., which is the figure we shall adopt in the meantime for the granitic layer.

For basalt of all types the new data lead to $A = 3 \cdot 7 \times 10^{-13}$ as an average, taking potassium to be present to the extent of ·8 per cent. In the summary of results given by JEFFREYS (Ibid.), this group of rocks is divided according to locality, and thus to a limited extent on the lines which we are following. The Pacific and Indian Ocean basalts have a low total radioactivity, owing to a small content of thorium. The « plateau basalts » have the least total radioactivity of JEFFREYS' four groups. If the term were restricted to the Oregon and Deccan lavas, the radioactive elements would be in almost the same proportions as are given for the whole group, and would lead to a value of A of about $2 \cdot 7 \times 10^{-13}$. As the basalts from these two regions are mostly of the tholeiitic type, one might conclude that this division of the basalt family was the less radioactive. One may hesitate however at present in

adopting so apparently improbable a result, and in drawing the temperature curve we shall employ the more general average for both the supposed basaltic layers.

The low value of the constant found for the quartz basalts may however be in one respect significant. If this type of rock had been formed by differentiation from olivine basalt, a higher, and not a lower degree of radioactivity might have been expected, as there are grounds for the belief that radium and thorium have a tendency to ascend in the magma column.

There is a further element in the temperature problem which has not yet, apparently, received much attention. In a study of the conductivity of granite H. H. Poole found a decided decrease in conduction with rising temperature (28). He was himself uncertain as to how far this was actual, and even whether it might not be entirely due to fracturing, on a microscopic scale, of the heated rock. There are some reasons for thinking, however, that the lowest conductivity measured, — ·00382 at 516° C, —, may be a genuine result. Ensor has found that slate, crystalline limestone, and quartzite undergo a like diminution of conducting power with heat (11). Eucken has shown the same to hold with single crystals of rock salt, calcite, and quartz (12). For quartz in particular between —190° and + 100° the conductivities in the two directions vary as rapidly as $\frac{1}{\theta}$, where $\theta$ the absolute temperature. Poole's low value at 516° is therefore not theoretically improbable and it would be wrong to overlook the possibility of such a variation in dealing with the granitic part of the crust.

The formulae given by the different experimenters are of the form $k = \alpha(1 - b\,\theta)$ where $\theta$ is degrees Centigrade. Such a formula however implies vanishing conductivity at a certain temperature, and it will be better to use a relation of the type $R = e(1 + f\,\theta)$, where $R$ is the thermal resistance, equal to $\frac{1}{k}$. The equation

$$R = 181\left(1 + \frac{\theta}{1160}\right)$$

combines Poole's result at 516° with two wich he obtained at 75° and 200°, before the rock had been further heated, and while there was thus less possibility of fracture.

The effect of the pressures to be met with in the crust on thermal conductivities has, on the other hand, been shown by Bridgman to be probably negligible (7). In constructing the temperature curve the method used will be as follows. It will be assumed that there is radioactive equilibrium, and the surface flow of heat (F) will, for reasons which have been advanced by one of us (3), be taken to be $2 \times 10^{-6}$ cal./cm.$^2$ sec. The upward flow of heat, and the resulting gradient, will then be calculated for every depth from the supposed values of A and the conductivities.

In the granitic layer the gradient is given by

$$\frac{\partial \theta}{\partial z} = R\,(F - Az)$$

or using the general formula for R

$$\frac{\partial \theta}{\partial z} \Big/ (1 + f\,\theta) = e\,(F - Az)$$

$$\ln \left(1 + f\,\theta\right) = ef\left(Fz - \frac{1}{2}\,Az^2\right) + \ln C$$

$$\theta = \frac{1}{f}\left[C \exp ef\left(Fz - \frac{1}{2}\,Az^2\right) - 1\right]$$

where C depends on the surface temperature. If this is zero one finds that the temperature is 384° at the base of the granitic layer, with the chosen values of the other constants. If the resistance is assumed to be invariable, and equal to 181, a temperature of only 332° results. The higher of these two values will be taken, although it is admitted that this introduces a slight element of uncertainty.

For basaltic rock Bridgman found a slight increase of conductivity between 30° and 70°. Poole obtained a comparatively constant value of about ·004 for all temperatures up to 600°. Bridgmann's result may perhaps be ex-

plained by the fact that his sample contained about 10 per cent of glass, as both the thermal and the electrical conductivities of glass are known to increase with heat. It is clear however that for the purpose of our calculation one cannot assume a variation for basalt in the same direction as for granite. The conductivity will be assumed to remain constant at ·004, corresponding to a resistance of 250, through both the supposed basaltic layers.

The evolution of heat will also be supposed to be the same for the two layers, as before stated, and to be $3{\cdot}7 \times 10^{-13}$ cal./cm³ sec. The temperatures to be inferred will then follow a parabolical curve, rising from 384° at 11 km. to 923° at 35 km., the depth assumed for the base of the olivine basalt layer.

It is now possible to compare the two curves. On the data which have been used they do not intersect. It will at once be seen, however, that there two points of closest approach. The one is at the base of the supposed olivine basalt layer, where they are 183° apart, and the other is at the base of the $P^*$ layer, where the actual temperature is 837°, and the distance is 200° (Fig. 3 A).

It might not at first sight appear as if these figures lent full support to the Joly theory. But one has to consider the inadequacy of the data. We have in the first place used a small value of the surface flow, denoted by F. The reasons for supposing that F is as small as $2 \times 10^{-6}$ cal./cm² sec. have been previously given by one of the authors (3), but this was chosen as a round figure, which might only be a first approximation to the truth. Values as large as 2·5 or even 3·45 in the same units had been used by previous investigators. If the constant had been assumed to be $2{\cdot}2 \times 10^{-6}$, temperatuses of 1097° and 982° would have been obtained at the two points, as compared with fusion temperatures of 1105° and 1037° (Fig. 3 B).

There is also the possibility that the values of A which have been used for the two rock groups are still too large. A figure of $5 \times 10^{-13}$ cal./cm³ sec. might have been adopted for the granitic layer, as suggested by Jeffreys' esti-

mate. Both types of basalt may possibly have a constant as low as $2 \cdot 7 \times 10^{-13}$, which would apply to the group

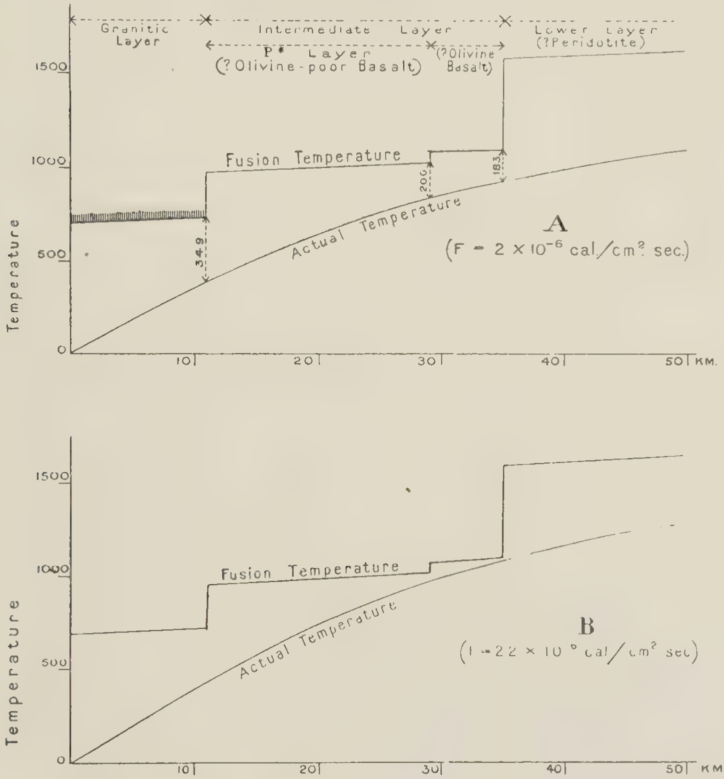


Fig. 3. — Curves of actual and fusion temperature, corresponding to different values of surface flow of heat, in non-orogenic area.

of « plateau basalts ». On these assumptions, without changing the value of F, temperatures of 1076° and 943° are arrived at for the two points.

## Onset of Vulcanicity.

A slight difference in the amount of the constants may thus be enough to ensure a close approach to fusion at one or other of the two levels. Actual fusion may then be brought about by some circumstance which is more

temporary. This might, for instance, be the oncoming of a period of lateral tension, and there will then be « pure melting » in the sense in which the term is used by DALY. The method of analysis which is being followed has an evident bearing on the preliminary process of an epoch of vulcanicity. The supposed lateral homogeneity of the crust has already been referred to. If this supposition is true, the temperature and fusion curves must also have a certain degree of lateral invariability. It follows that if, at any depth, there is a close approach between the two curves, this approach will not be local, but must extend in the horizontal direction, probably for hundreds of kilometres.

The conception to which this leads is that of a sheet-like magma reservoir, almost constant in depth, and extending for long distances at a certain critical level. We attach some importance to this idea, which of course is not original. If magma basins have not a wide lateral extent, the facts of dyke formation are almost inexplicable. The Cleveland Dyke is one of the Mull swarm, and the distance from Mull to Cleveland is about 370 kilometres.

It has been suggested by Dr. BAILEY that the swarm of dykes has been fed laterally from the Mull centre. Dr. RICHEY on the other hand has given reasons for doubting this, and considers that the method of intrusion has been vertical. This discussion has hardly yet been referred to in print, though it is of evident importance in the present connection. If Dr. RICHEY's contention is true, it strongly supports our supposition.

The bulk of material in the Cleveland Dyke is so large that its abstraction would partly empty any local and more or less vertical reservoir. Such a basin must have been simultaneously filled from beneath. Moreover there are dykes, such as the east and west quartz-dolerites of Scotland and Northern England, which it is difficult to connect with any centre. Even if intrusion is vertical, the fractures which it follows may spread laterally from some centre of weakness, and it is easy to see how dykes, in certain cases, may be concentrated into swarms.

We shall assume that the conception is true, and that every volcanic episode begins with the melting of a horizontal sheet. In a normal portion of the crust the formation of an olivine rich basaltic magma, and of an olivine poor, or tholeiitic magma, would then seem to be both possibilities. On the particular assumptions which have been made, the former eventuality is, however, the more probable. With the method of extrusion of these magmas we are not, at present, attempting to deal.

If the layers are as sharply defined as has been shown, it seems unlikely that there can be melting of both at once, though not perhaps entirely impossible. There is, however, another alternative. The $P^*$ layer, here assumed to be olivine poor basalt, must be definite in composition, and vertically uniform. But the olivine rich layer may not be so definite. There may, in fact, be a gradation downwards from the base of the $P^*$ layer, through material containing more and more magnesia, etc., and less silica, ending perhaps with a sudden break, where the « lower layer » is reached. In these circumstances the fusion diagram might not contain the third step which has been shown, and the two curves, instead of cutting at one or two points, might more or less osculate. There might then be melting at more than one level, with an alternation of the types of magma extruded, as has happened in Mull. Whether this or the former hypothesis is to be adopted may perhaps be settled by some further advance in seismology.

On either hypothesis the formation of these magmas is restricted to within definite limits of depth. It seems highly improbable that, if melting takes place within the $P^*$ layer, it can do so at any great distance above the base. At higher levels the two curves diverge somewhat rapidly, and the reasons for supposing that fusion is impossible, where they are normally more than 50° or so apart, have already been given. The curves again approach at the base of the granitic layer, but at that point the distance must be at least about 200°. In the non-orogenic areas considered therefore, it is unlikely that there can be

primary fusion within 25 km. of the surface. If the $P^*$ layer did not extend to that depth, it could not fuse. Even allowing for the uncertainty of the data, these statements are probably correct.

In the downward direction formation of basalt magma is possible as far as the supposed break at 35 km. The crystalline or glassy nature of the basaltic layers does not affect the depth of fusion. If these layers are glassy the provenance of olivine basalt can be explained by supposing, as JEFFREYS has done, that the $P^*$ layer is tachylyte of like chemical composition. The olivine-free basalts must then be derived from some higher level, unless they are products of assimilation or differentiation. Reasons have been given for discrediting the latter hypothesis. It might be more difficult to allow for an extra thickness above the intermediate layer than at its base, though this is a point which must be left to seismologists. If, however, an olivine-free basalt layer occurred above the intermediate layer, it could not be subject to primary fusion, in an unthickened crust. This can easily be seen from the diagrams (Fig 3).

For these reasons we prefer to suppose that the material at the levels considered is crystalline, and that the $P^*$ layer has the composition of olivine-free, as opposed to olivine-bearing basalt. It is possible that this layer is entirely absent under some parts of the oceans. This cannot be proved at present, because of the want of island observing stations. If it were found to be true, the restrictions in distribution of the more acid type of basalt would be very easily explained on our hypothesis.

### Possibility of an Ultrabasic Magma?

There is a further consequence of the line of reasoning followed which it is important to indicate. Just below the break at 35 km. the curves may recede suddenly to 500° or more apart, if the layer above is unfused, as there is about 500° of difference between the melting points of peridotite and olivine basalt. The upward flow of heat at

this depth was $\cdot 674 \times 10^{-6}$ cal./cm². sec., according to our first set of assumptions. It may be more than this, but it can be shown that it cannot possibly be greater than $1 \cdot 3$ in the same units. If it is even as large as this, the surface flow must considerably exceed the $2 \cdot 2 \times 10^{-6}$ cal./cm². sec. which is assumed in Fig. 3B. and even on the most unfavourable hypothesis, the temperature at the base of the olivine basalt layer must probably lead to melting. The statement will hold even if the joint thickness of the granitic and basaltic layers is not more than 30 km. If radioactive equilibrium is assumed the calculation of any particular case is simple, and a general proof of the conclusion need not be given.

A flow of heat of $1 \cdot 3 \times 10^{-6}$ cal. / cm². sec. corresponds to a temperature gradient of $32 \cdot 5^{\circ}$ per kilometre, if one supposes the lower layer to have the same conducting power as basalt. The fusion temperature, below the break increases downwards, however, at some $3^{\circ}$ per kilometre, and $30^{\circ}$ per kilometre is about the most rapid rate at which the two curves can here approach. This rate of approach may not, however, be maintained. One may follow the method of calculation which has been so far applied, assuming that even at this depth there is radioactive equilibrium. One may apply the constants which result from averaging JEFFREYS' collected data for the class of « peridotites , etc. ». These give a radium content of $0 \cdot 85 \times 10^{-12}$, and a thorium content of $0 \cdot 65 \times 10^{-5}$, leading to a value of $A$ of about $3 \cdot 5 \times 10^{-13}$. Or one may use the results for dunite, which give $A = 1 \cdot 7 \times 10^{-13}$. In the former case the curves will fail to meet, although there may be a close approach at a depth below the break of 34 km. In the latter case the lower layer must have a surface fusion temperature of about $1700^{\circ}$. If the conductivity is the same as that of basalt, and the curves do not touch above the break, they will not meet again less than 30 km. further down. It has been assumed that the flow of heat at the base of the olivine basalt layer is as large as the figure mentioned, but we regard this

as highly improbable. If the flow were there no greater than $10^{-6}$ cal./cm$^2$. sec., and the other assumptions were valid, the curves could never again approach so closely as to admit of fusion.

It appears therefore to be doubtful whether any peridotite magma can be formed by what may be denoted as primary fusion. If it can, it must originate at least 60 km. below the surface, and it is difficult to see how it can reach the surface rocks without contamination. This conclusion is in keeping with the results arrived at on different grounds by Bowen and Schairer.

If the conclusion is true, the lower layer may be something of which there are nosamples at levels near the surface, and the hypothesis that it is ordinary peridotite, or dunite, may need reconsideration. Certainly this layer cannot produce as much heat as has been mentioned above, if there is the condition of radioactive equilibrium. If it did, the temperature gradient would soon become zero when followed downwards, implying a total absence of radium and thorium from the levels below The difficulty may be met, to some extent, by supposing the composition to be similar to some of the many classes of stony meteorites. Some of these are peridotites, but the materials as a whole are known to have much smaller radioactive constants than ordinary peridotite, or dunite. The olivine of meteorites is a magnesian variety, and the melting point may be about the same as has been adopted for peridotite. In such a material the two curves might approach more rapidly, but they could not meet at less than 18 km. beneath the top of the layer, and more probably intersection, if it occurred would be further down.

## Thermal Effects of Orogenesis.

We wish next to consider the effect on the two curves of the thickening of the crust in regions of recent orogenesis. It is uncertain how many of the crustal layers the thickening affects. It will be assumed for the meantime that

noly the granitic, or Lewisian layer, is affected, while the $P^*$ layer, and the possible olivine basalt layer, maintain their thickness, but are forced downwards to a lower level.

The amount of thickening of the granitic layer may then be roughly estimated from the gravitational anomaly. Kossmat shows a broad zone in the Alps to have a negative Bouguer anomaly of over 100 milligals, locally exceeding 200 milligals (25). One may assume a specific gravity of 2·75 for the granitic layer, and of 3·4 for the lower layer. 100 milligals then corresponds to a thickening of the former to the extent of 3·7 km., and 200 milligals to 7·4 km. If the granitic layer were thickened to any extent *at the expense* of the basaltic layers, the amounts calculated would be more. We shall assume that in this region the granitic layer has the general thickness of 18 km., as contrasted to a normal value of 11 km.

The effect on the temperature curve which is produced by an orogenetic period will depend on the length of time which is necessary for its completion. If the movement were relatively sudden, the base of the granitic layer might be displaced downwards to 18 km., without any corresponding rise in temperatures. If there were a homogeneous strain of the material, the temperature gradient, and the initial surface flow of heat, might then be diminished in the ratio 18:11. If the normal surface flow is $2 \times 10^{-6}$ cal./cm². sec., that in a newly formed mountain range might be no more tham about $1{\cdot}2 \times 10^{-6}$. A conception similar to this was put forward some fifty years ago by Osmond Fisher (13). He considered the granitic layer to be floating on molten basalt, which was exactly at its melting point. The temperature at the base of the layer was therefore independent of its thickness. In support of this idea he quoted the observations made in Alpine tunnels, which certainly indicate a gradient somewhat under the average.

It now seems probable, however, that if there is so large a diminution of surface flow, it cannot be a lasting one. The condition of radioactive equilibrium may well be disturbed by mountain formation, but it will tend, sooner

or later, to reestablish itself. With the constant which has been taken for the granitic layer, an original surface flow of $2 \times 10^{-6}$ cal./cm². sec. will then be increased to about $2 \cdot 4 \times 10^{-6}$. It is therefore worth while to reexamine the data given for Alpine tunnels, to see whether they indicate a flow of heat which is greater or less than normal.

The low gradients are at least partly accounted for by high conductivities, but to what extent this is the case is difficult to estimate. Schists and gneisses are certainly better conductors than their unmetamorphosed equivalents. This is particularly the case for quartzose schists, but it applies also to pelitic rocks, and probably to calcareous rocks and marble.

In the deepest part of the Mt Cenis tunnel the gradient was 20° C. per km., according to the observations of GIORDANO (14). The average is, however, probably more than this, and was given as 1° F. in 79 feet, or 23° C. per km. by EVERETT, who is quoted by PRESTWICH (29). The rocks are grey schistose « calcari », with some talc and many veins of quartz. Limestone has usually a conductivity of about ·005 ; that of marble may be as high as ·00714, as has been found by EUCKEN (12). The flow of heat which is indicated by the gradient will therefore lie somewhere between $1 \cdot 15 \times 10^{-6}$ and $1 \cdot 6 \times 10^{-6}$ cal./cm². sec., depending partly on the exact meaning of the word « calcari ».

Particulars with regard to the Simplon tunnel are recorded by SCHARDT (30), and NIETHAMMER (27). In this case careful estimates were made of the average surface temperatures at a number of points directly above the line of the tunnel, by means of thermometers sunk a certain distance into the solid rock. From comparison of these results with those obtained in the tunnel NIETHAMMER gives the average gradient for the whole length as 25° per kilometre. In one part howerer the underground temperatures were obviously reduced by the influence of cold water which had percolated from above. Above one particular stretch of tunnel the gradient was as high as 34·4° per

kilometre. NIETHAMMER attributes the relative warmth of this section to two causes:- the absence of percolating water, and the fact that the banding of the gneisses here nuns parallel to the surface.

The effect of water on the temperatures might be twofold. In the first place it must slightly increase the conductivity of the rocks which it permeates, and thus a dry sector of tunnel might be relatively warmer than a wet one. KOENIGSBERGER and MÜHLBERG however estimate the increase for granite and gneiss as being no greater than 10 per cent (24). The other effect is one which will only be of special importance in mountainous districts. The downward percolation must be limited by the extent of the surface relief. To affect the gradient at any level the water must obviously be provided with a means of lateral escape below the point of observation. The abstraction of heat may then be of importance. This may readily be seen as follows. Suppose the rock to be so permeable that the whole of an annual rainfall of say 1 metre is absorbed, and finds its way downwards to a level where the temperature is $10^{\circ}$ higher than at the surface. There would then be an abstraction of heat from the solid of about $3 \times 10^{-5}$ cal./cm.$^2$ sec., or about 15 times as much as we have been supposing to be normally due to an upward flow. It seems to follow that only a very small fraction of the annual precipitation can penetrate to the depths which are being considered. Otherwise hardly any gradient of temperature could have been observed in the tunnels at all.

Even a small fraction might be important, and the inference might be that the nearest approach to the gegeneral sub-Alpine gradient would be found in the driest part of a tunnel. The other consideration by NIETHAMMER has however to be examined. In foliated rocks, with parallel mica flakes, the conductivity is smaller in the normal direction than along the schistosity. The ratios of the conducting powers for various types of gneiss, etc., have been estimated by KOENIGSBERGER and MÜHLBERG (Ibid.) and their figures seem to show that a variation in gradient

from 27° per km. to 34·4° per km. might be due to this cause.

Apart from the sector mentioned, the banding met with in the tunnel was usually inclined, and in one part it was vertical. The rocks are mainly gneisses and « schistes lustrés ». Koenigsberger and Mühlberg experimented with ten samples, of different types, from different parts of the tunnel, which may perhaps have been fairly representative. The conductivities ranged from ·0043 to ·0073, the average being ·00568. These amounts were measured parallel to the schistosity. If the average is taken along with a gradient of 27° per kilometre, the resulting flow of heat is $1 \cdot 53 \times 10^{-6}$ cal./cm² sec. This assumes that the banding is everywhere vertical, but when this cause of error is set off against the possible effect of percolating water, the result may not be actually too high.

The mean gradient of temperature above the Gotthard tunnel was taken by Prestwich to be 1° F in 57·8 feet, or 31·5° C. per km. (29), as deduced from Stapff's observations There are however great variations in the observed gradient, which do not seem to be entirely explained either by varying conductivities, or by the shape of the ground. The flow of heat appears to be a doubtful quantity, though it is possibly greater than in the other two cases discussed.

Outside the orogenic areas the average apparent flow has been found by one of us to be about $1 \cdot 5 \times 10^{-6}$, as calculated from a few of the many observations in boreholes (3). The data are so far very meagre, and the figure of $2 \cdot 0 \times 10^{-6}$, which has till now been used in this paper, was derived from that mentioned by making certain allowances. About 10 per cent was added to the former amount on account of the supposed inadequacy of the experiments, as it is impossible for a boring operation not to produce a certain lowering in the temperature of the adjacent rock. The amount $\cdot 367 \times 10^{-6}$ cal./cm² sec. was then added for a presumed glacial effect, as the increase of temperature at the end of the ice age must still be effective in causing

a general reduction of surface gradients. Similar considerations must affect the Alpine results, and the glacial effect must in fact be somewhat greater than in an area of unmetamorphosed sediments, owing to the greater conductivities.

When these allowances have been made, it is hardly possible to decide whether the data given above point to a greater or less loss of heat in the Alps than the $2 \cdot 0 \times 10^{-6}$, which has been taken to be the average in non-orogenic areas. Two things, however, may, we think, be affirmed:

(1) The flow is greater than would have occurred just after a sudden thickening of the granitic layer by a homogeneous strain, from 11 to 18 km., and

(2) it is less than the equilibrium amount.

It may be about half way between the two extremes, or a little nearer to the position of equilibrium. We infer that if the layer was suddenly thickened, in the way which has been supposed, enough time has since elapsed to enable the geoisotherms to rise considerably. The downward bend may not yet have been replaced by an upward bend, but the lines must have straightened out.

With the reestablishment of radioactive equilibrium the layers at all levels will rise to higher temperatures than they had before the orogenesis. The effect will, howerer, be a progressive one; it will influence at first only the granitic layer and that part of the $P^*$ layer which lies immediately beneath. It will only very gradually penetrate to the base of the $P^*$ layer, and the supposed olivine basalt below.

On the assumptions which have been made as to the nature and conductivity of the different layers, the rise in temperature at any level is difficult to estimate. It is only by supposing than both the conductivity and the volume heat capacity are constant, throughout all the layers, that definite values can be reached. We shall make these suppositions and for the meantime only the temperature variation which has to do with the reestablishment of equi-

librium will be considered. The method of calculation is as follows.

In a condition of a radioactive equilibrium there is the relation

$$\frac{\partial}{\partial z}\left(k\,\frac{\partial\theta}{\partial z}\right) = -A$$

where $\theta$ is temperature, $z$ depth, $k$ the conductivity, and $A$ as before the volume evolution of heat. When the homogeneous strain which affects the granitic layer is applied, the quantity on the left is, as we suppose, more or less suddenly reduced in the ratio $18^2 : 11^2$, or $1 : \cdot 373$. The levels below are not similarly affected, and the whole would now only be in equilibrium if the two following conditions were satisfied :

(1) If the granitic layer, instead of having the radioactive constant $6 \times 10^{-13}$ cal./cm$^3$ sec., as before, had a volume evolution of only $\cdot 373$ times this amount, or $2 \cdot 24$ in the same units, and

(2) If there were a « plane sink » of heat, at a depth of 18 km., sufficient to account for the change in value of $k\,\frac{\partial\theta}{\partial z}$ which now occurs at this level.

These two conditions are not satisfied, and the temperatures which actually result may be obtained by adding to the initial temperatures :

(1) Those which would be caused, in the semi-infinite solid, if it were initially everywhere at zero, by a uniform distribution of radioactivity down to 18 km., with a volume heat production of $\cdot 627$ times the original amount of $A$ in the granitic layer, or $3 \cdot 76 \times 10^{-13}$ cal/cm$^3$ sec., while there was no radioactivity below, and

(2) Those which would be caused in the semi-infinite solid, at zero temperature, by a « plane source » of heat at a depth of 18 km., numerically of equal strength to the supposed sink.

The two additions begin to act when $t = o$, immediately after the imposition of the strain. They may be de-

noted by $\theta_1$ and $\theta_2$, and each is a function of $z$, the depth from the surface, as well as of $t$. The form of $\theta_1$ has already been calculated by JEFFREYS (20). If the volume heat capacity of granite is $\cdot 65$, on our hypothesis there is at first a steady rise in the temperature of the granitic layer, which is independent of depth, except close to the boundaries, and is of amount 1° in 54,000 years. For longer periods it is necessary to use JEFFEREYS' formula, in a modified form, which leads to the result [1]).

$$\theta_1 = \frac{Bh^2 t}{2\,k} \left\{ \left[ 2 \operatorname{erf} \frac{z}{2\,h\sqrt{t}} - \operatorname{erf} \frac{z-a}{2\,h\sqrt{t}} - \operatorname{erf} \frac{z+a}{2\,h\sqrt{t}} \right] \right.$$

$$+ 2 \left| \frac{2\,z^2}{4\,h^2 t} \operatorname{erf} \frac{z}{2\,h\sqrt{t}} - \frac{(z-a)^2}{4\,h^2 t} \operatorname{erf} \frac{z-a}{2\,h\sqrt{t}} - \frac{(z+a)^2}{4\,h^2\,t} \operatorname{erf} \frac{z+a}{2\,h\sqrt{t}} \right|$$

$$\left. + \frac{2}{\sqrt{\pi}} \left[ \frac{2\,z}{2\,h\sqrt{t}}\, e^{-\frac{z^2}{4\,h^2 t}} - \frac{z-a}{2\,h\sqrt{t}}\, e^{-\frac{(z-a)^2}{4\,h^2 t}} - \frac{z+a}{2\,h\sqrt{t}}\, e^{-\frac{(z+a)^2}{4\,h^2 t}} \right] \right\} + f\,(z)$$

Here $B$ is the quantity $3 \cdot 76 \times 10^{-13}$ cal./cm³ sec., $h^2 = \dfrac{k}{c\,\rho}$, where $c$ is the specific heat and $\rho$ the density, both $k$ and $c\rho$ being assumed to be constant,

$$a = 18 \text{ km.} = 1 \cdot 8 \times 10^6 \text{ cm.},$$

and

$$f\,(z) = \frac{B}{2\,k}\,(2\,a\,z - z^2) \qquad (z < a)$$

$$f\,(z) = \frac{B}{2\,k}\,a^2 \qquad (z \gtreqless a)$$

Tho calculate $\theta_2$ it is necessary to assume that the solid is infinite, and that the plane source at 18 km. be-

1)
$$\operatorname{erf} x = \frac{2}{\sqrt{\pi}} \int_0^x e^{-u^2}\, du$$

low the original surface is balanced at 18 km. above that level by a plane sink of numerically equal amount. If $C$ is the evolution of heat in unit time and area along the plane source, it is easy to show that

$$\theta_2 = \frac{C}{k} \left\{ \frac{h\sqrt{t}}{\sqrt{\pi}} \left[ e^{-\frac{(z-a)^2}{4h^2t}} - e^{-\frac{(z+a)^2}{4h^2t}} \right] \right.$$

$$\left. + \frac{1}{2} \left[ (z-a) \operatorname{erf} \frac{z-a}{2h\sqrt{t}} - (z+a) \operatorname{erf} \frac{z+a}{2h\sqrt{t}} \right] + g(z) \right\}$$

where

$$g(z) = z \qquad (z < a)$$

$$g(z) = a \qquad (z \geqq a)$$

To estimate C one must assume some definite value for F, the surface flow before orogenesis. If this was $2 \times 10^{-6}$ cal./cm² sec., the flow at a depth of 11 km. was $1{\cdot}34 \times 10^{-6}$ according tho our first assumption. This becomes reduced in the ratio *18 : 11* within, while it remains constant, as we suppose, just below, the granitic layer. The source of heat must therefore be of amount $\cdot 521 \times 10^{-6}$ cal./cm² sec.

The formulae will, of course, at best be only approximate. The preliminary strain may not be homogeneous, and inconsistent assumptions have been made with regard to $k$. For high temperatures, however, $k$ for granite may have nearly the value of ·004 which has been used for basalt. Formulae for the specific heat of both these rock-types are given by H. H. Poole (27). Allowing for a certain correction which he indicates, and supposing the density to be 2·65, the volume specific heat of granite will be ·46 at 0°, ·70 at 300°, and ·76 at 500°. For basalt Poole's formula leads to a maximum specific heat per gram of ·258 at 530°, with diminution at higher temperatures. The formula is not intended for application to the range of temperatures to which the basaltic layers must be subject. Daly, basing his estimates on the work of Barus, and its discussion by Vogt, gives about ·250 for crystalline basalt

at 500°, and about ·270 at 1000° (8, 4, 33). These quantities would correspond to volume specific heats of about ·750 and ·800. It will be convenient for our purpose to use a value of ·779 for $c\rho$, with ·004 for $k$, for both granite and basalt, and for the « lower layer ». These figures lead to simplicity of calculation for periods of 5 million years, at the depths we require to investigate, and they may only be seriously wrong for the upper part of the granitic layer.

On these assumptions the rise of temperature above that which obtained at corresponding levels before orogenesis is shown in the following table. The times are reckoned from the period of homogeneous strain, which is supposed to have been abrupt. The lack of accuracy which results from the nature of the assumptions will only affect the granitic layer, to any great extent. At lower levels it is likely that the temperatures calculated have only to be slightly increased, if the more general data are correct.

| $10^6$ years × | Granitic Layer | | Olivine-free Basalt Layer | | Olivine Basalt Layer |
|---|---|---|---|---|---|
| | 9 km. | 18 km. | 27 km. | 36 km. | 42 km. |
| 5 | 68° | 100° | 34° | 8° | 2·4° |
| 10 | 100° | 146° | 71° | 30° | 14° |
| 15 | 118° | 175° | 101° | 51° | 31° |
| 20 | 131° | 196° | 124° | 71° | 47° |
| 25 | 140° | 212° | 142° | 88° | 62° |
| | — | — | — | — | — |
| 45 | 161° | 250° | 190° | 138° | 110° |

Supposed increases of temperature, at depths shown, after orogenesis.

The results for periods of 10 million years, and 45 million years after orogenesis, are shown graphically in Fig. 4. The increases which have been calculated for depths of 36 and 42 kilometres must be added to the temperatures supposed previously to exist at the bases of the olivine-free basalt, and the olivine basalt layers respectively. These were 837° and 922°, according to our first set of assumptions, while the corresponding fusion points are now 1058° and 1126°. It will be seen that from about 10 million years after orogenesis conditions become reversed, so that there is a closer approach to fusion at the base of the olivine-free layer, instead of the olivine bearing layer, as before.

The effect would be more marked if the relative thickness of the upper division of the intermediate layer vere smaller. A factor not so far considered is the abnormal thickness of sediments, in the « geosyncline » which is believed to have formed a preliminary condition for every instance of mountain-building. This in itself would tend to a rise in temperatures before the beginning of orogenesis, spreading downwards from the original surface of the crust. The increase might persist till long afterwards, and there would be a retardation in depth, as in the case described above. It might therefore have the same bearing upon the magma problem.

The distortion of the granitic layer under pressure, during orogenesis, must also result in a certain evolution of heat. This has so far been neglected. Suppose that a cubic centimetre of rock is deformed by pressure in the X direction. It may be assumed that it is unable to expand in the Y direction, but that in the Z or vertical direction there is no restricting force. If, under these circumstances, the cube is distorted to a parallelopiped with sides $\frac{1}{a}$, $1$, and $a$ cm. in length, under uniform pressure P, the expenditure of energy is $P \ln a$. All, or nearly all, of this energy must appear in the form of heat. If $J$ be $4 \cdot 16 \times 10^7$ ergs, $\rho$ the density, and $c$ the specific heat of the affected rock, then apart from conduction the rise of temperature

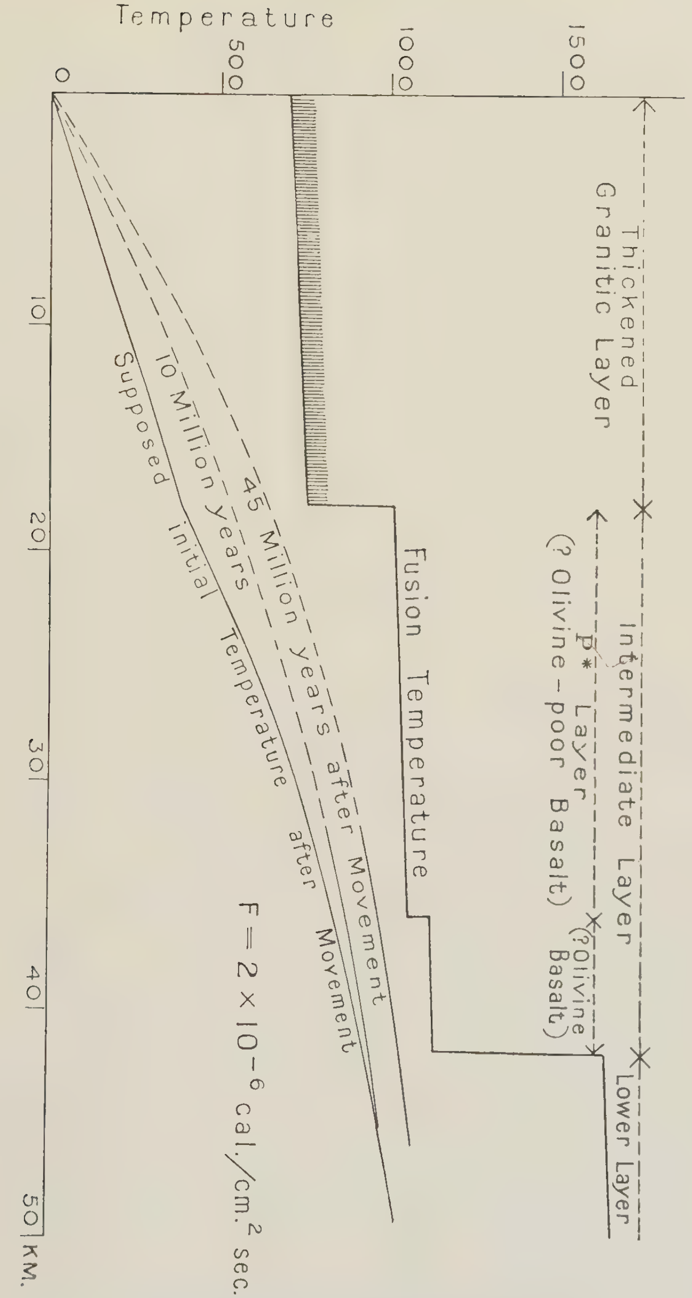


Fig. 4. — Curves of fusion temperature, and of actual temperature at different periods, in non-orogenic area.

will be $\frac{P \ln a}{J c \rho}$. In the supposed homogeneous strain $a$ was $\frac{18}{11}$, and $c\rho$ must be something between ·5 and ·8. If $P$ be the same as the ordinary breaking stress of granite, about $8 \times 10^8$ dyne. cm.$^{-2}$, the rise of temperature will be from 12° to 20° for this amount of distortion. But the actual strain is non-homogeneous, and probably the numerator of the expression should be increased. The stresses at a depth from the surface may also be greater than those which would give rise to fracture in the laboratory. The lateral pressure $P$ will be partly balanced by a vertical pressure $R$, and the expression becomes $(P - R) \ln a/Jc\rho$. ADAMS and BANCROFT's experiments have shown that, in such circumstances, $P - R$ may be as much as 12 times the surface strength, without causing rupture. The actual orogenetic pressures can at present only be guessed at. They may not be nearly so large as has been suggested, but in any case the evolution of heat may be considerable. On present assumptions this will be confined mainly to the granitic layer. The rise in temperature will originate in this layer, and, as before, it will be gradually conducted down.

Little can as yet be inferred about the behaviour of the intermediate, or of the lower layer, during orogenesis. JEFFREYS has supposed that the intermediate layer is at first thickened, but that long after the surface movements it becomes thinned, and there is strong reason to believe in the latter assumption (21, p. 282 and pp. 295-6). A general thinning of the intermediate layer, which was homogeneous, and did not affect the lower layer, would have the following thermal results. The plane source of heat, which we have supposed to exist at 18 km. depth, would be intensified. The layer itself would at first be mechanically heated, but would afterwards react as if it had superimposed negative radioactivity, while its base would behave as a « plane sink ».

The later effect might possibly more than counterbalance the earlier, so that there would be retardation of any

tendency to vulcanicity, and if the « intermediate layer » of the supposition included a basal olivine basalt member, fusion would take place preferentially in the member above.

Jeffreys' reason for supposing that the intermediate layer becomes thinned is briefly as follows. Old mountain areas in the course of time become peneplanated, and sink to near sea level. As the granitic layer does not appear very widely at the surface, there must have been a limit to surface erosion, and gravitational adjustment cannot as a whole have been effected by any bodily elevation. The only alternative is to suppose that the intermediate layer, (and perhaps to some extent the granitic layer itself), has been thinned by an outward flow. The period of such a movement is supposed by Jeffreys to be long subsequent to that of the orogenesis. The interval may, however, in any case, be only relatively a long one. It may be comparatively short, when reckoned on the geological time scale.

The Caledonian movements in Scotland probably began in Ordovician times, but they are supposed to have been mainly Silurian. They were practically completed before Devonian times, and probably to a large extent before the last, or Downtonian, stage of the Silurian. There is some reason for thinking that when the Carboniferous period began, the Scottish mountains were already peneplanated. This reduces the duration of the process to about 100 million years, instead of the 300 million years suggested by Jeffreys. Within this interval the thinning which has been spoken of must have been entirely complete. It must therefore have begun fairly early, but whether it was early enough to account for the relative acidity of the Scottish Old Red Sandstone basalt or andesite lavas is a more doubtful point. The time scale which is indicated by this example should in any case be noted. The whole life of the Caledonian mountain range may have been less than 150 million years.

The relative abundance of olivine-free or olivine-poor lavas in mountainous regions is one of the facts which it

has been the object of this paper to explain. It has been seen that there are four possible causes which may combine to influence the temperature curve in the required direction. There is first the blanketing effect of a more than usual thickness of sediments, which are also in themselves to some extent radioactive. There is next the heat given out during distortion. There is thirdly the radioactive effect of the thickening of the granitic layer, which has been investigated in somewhat greater detail. The three causes are not strictly contemporaneous, but they may all combine to form a « heat-wave ». By this is meant an accession of relatively higher temperature in the granitic layer, whieh will spread itself out, and in so doing will gradually travel downwards. In addition one has to take into account a possible thinning of the intermediate layer. This may not take place till some time after orogenesis, but, when it does, it will tend to prevent any melting of the more basal part. There are, of course, other possibilities besides those which have been dealt with. Some of these might not produce the effect in question, but a contrary one. If, for instance, the entire intermediate layer was originally thickened along with the granitic layer, but the lower layer was not so affected, the base of the supposed olivine basalt layer would act as a source of heat. There is, however, a good reason for supposing that this view of the orogenetic process is erroneous. Before movement began the lower part of the intermediate layer, lying then at a depth of from say 25 to 35 kilometres, was all comparatively near to its point of fusion. This statement does not apply to the upper part of the lower layer, and the material above 35 kilometres would thus, in all probability be the more readily deformed. The levels from 25 to 35 km. are in fact to be regarded as a zone of weakness. They can hardly have borne any of the lateral stress which gave rise to mountain building. It seems more probable that their rôle was purely passive. They must either have been pushed downwards whithout alteration, or squeezed out between the more resistant layers above and below.

Whatever may be the case as to the basaltic layers, the thickening of the granitic layer is not open to doubt. This by itself, as has been seen, will favour the production of an acid type of magma. It is in this layer that the heating effect is at any rate the most pronounced. The temperature curve can hardly at any time have the form attributed to it by De Lury (9). This would be improbable, even after orogenesis, and impossible in an unthickened crust. But, for millions of years after an epoch of mountain building, the temperature of the upper part of the intermediate layer will rise, in relation to that of the lower. This may lead to fusion at higher levels, where presumably there may be more siliceous material. The principle is independent of all but the most general assumptions, and we suggest that it is the reason why orogenetic areas are characterized by olivine-free, or tholeiitic lavas.

### Fusion of the Granitic Layer?

A further consequence of the line of reasoning which has been followed in this paper remains to be dealt with. In an unthickened sector of the crust actual temperatures at the base of the granitic layer may fall short of fusion temperatures by perhaps about 350°. When equilibrium becomes reestablished in a thickened sector, this figure will at least be much reduced. It has been seen that the surface flow may then be about $2{\cdot}4 \times 10^{-6}$ cal./cm². sec., although at the base of the layer the amount may not be greater than it was before orogenesis. If one assumes that the granitic material has a constant resistance of 181, corresponding to a conductivity of ·0055, the new datum leads to a temperature of 609° for the supposed base at 18 km. If however one uses the formula which we have deduced from Poole's experiments the temperature inferred is 796°. This involves a good deal of extrapolation beyond the limit of the experiments, but so much might not be needed, as probably the rock would melt before such a temperature was reached.

The possibility of fusion appears to depend mainly on two things. There is first the accuracy of the conduction formula, and secondly the question whether the thickened condition of the crust can persist for long enough. The table given on p. 71 is not accurate for the depth considered, but it shows that, even in 45 million years, full equilibrium will not nearly be reached. It has been seen, however, that some melting takes place in granite, under surface conditions, at 570°. The corresponding figure, at a depth of 18 km., would be 624°. This degree of heat would be attained much sooner, and on the whole the assumption that there may be melting of the granitic layer appears to be justified. It has at least to be taken into consideration unless the decrease in the conducting power of granite at high temperatures can be disproved.

## Conclusions.

The reasons for supposing that there may be formation of primary granitic magma have been stated in the former part of this paper. This conclusion, it now appears, is not contradicted by anything at present known as regards the geophysical evidence. Primary fusion of the granitic layer can, however, only take place in orogenic areas, according to any possible hypothesis, and this easily explains the observed limitation in the distribution of granite stocks and batholiths.

Apart from this question the principal object of the paper has been to explain the distinction, in type and in distribution, of the two main classes of basalt. Concerning this two suggestions have been made, but it is possible to admit a third. It has been supposed :

*a)* that olivine basalt forms a distinct layer, between the $P^*$ level and the underlyng $P_n$ level, the latter being possibly occupied by peridotite, or

*b)* that the layer, although in the position referred to, grades upwards into the more acid material of the $P^*$ level, and is thus not so distinct.

The third hypothesis is

*c)* that the intermediate layer consists entirely of tholeiitic or olivine-poor basalt, and that olivine basalt is derived from the upper part of the lower, or $P_n$ layer, where it exists in the form of eclogite.

That the lower layer is eclogite has been maintained by GOLDSCHMIDT, and was believed at one period by HOLMES, and the theory is perhaps supported by JEFFREYS' collected data as regards the radioactivity of this rock (22). These lead to an average heat evolution which is considerably less even than that for dunite. In this way the difficulty of reconciling the low maximum value of the flow of heat, which can be assumed for the top of the layer, with the condition of radioactive equilibrium, might be to some extent removed. It may not, of course, be possible to infer the radioactivity of the supposed layer from that of surface rocks of similar type. If not, the material in depth may be even less radioactive. To speculate further, it would be necessary to know the melting point of eclogite, and in particular of that variety which is most similar in chemical composition to olivine basalt. If the temperature of fusion depended more on the chemical than on the mineralogical composition, the objections to supposing that there can be melting of the lower layer might be overcome.

For lack of this information, and of other data, we have confined our investigation to suppositions *a)* and *b)*. The lines of reasoning followed are to be regarded as exploratory. If olivine basalt is derived from the lower layer the bearing of orogenesis on the magma problem will need to be restated, but it seems probable that the conclusions will be, on the whole, the same. We think that the $P^*$ layer may be regarded with good reason as consisting of tholeiitic basalt, but that, as regards olivine basalt, it is difficult at present to decide between hypotheses *a)*, *b)*, and *c)*.

We wish, finally, to express our thanks to Prof. A. HOLMES, and to Dr. H. JEFFREYS, for kindly answering enquiries connected with these investigations.

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N. A. CRITIKOS

# Journal des phénomènes éruptifs du volcan des Kaménis (Santorin) de 1925-1926 et de 1928.

*(Avec une planche)*

## Introduction.

Au sujet de la dernière éruption du volcan des Kaménis (Santorin) de 1925-1926 et l'éruption parasitaire de celle de 1928 nous avons déjà publié les notes suivantes :

« *Sur des phénomènes sismiques produits avant et depuis l'éruption du volcan de Santorin 1925* » (C. R. de l'Académie des Sciences 181, p. 923).

« *Sur la sismicité des Cyclades et de la Crète* » (Annales de l'Obs. Nat. d'Athènes t. IX, 1926) [1].

« *Impression d' une visite à Santorin* » (Ciel et Terre. Année 1926 p. 99).

« *Phénomènes sismiques qui ont précédé la récente activité (1928) du volcan de Santorin* » (Praktika de l'Académie d'Athènes 3, 1928, p. 450).

[1]) A l'occasion de la présente publication nous jugeons utile de faire la remarque suivante au sujet de la carte géographique jointe à cette note, sur laquelle sont marqués les centres sismiques déterminés par nous, et sur laquelle aussi est mise en évidence la distribution des centres volcaniques dans la Mer Egée méridionale.

Pour tracer cette carte nous nous sommes servis de la carte publiée dans la note des M. Mrs Friedlaender und Sonders « *Eine Studienreise nach den Vulkaninseln Griechenlands* » (Zeitschrift für Volcanologie, VIII, 1924, p 4), qui est à quelques modifications près, une réproduction de l'ancienne carte manuscrite dressée par M. C. Kténas ; cette dernière se trouve dans la salle publique du Laboratoire de Pétrologie de l' Université d'Athènes (v. C. Kténas « *Le groupe d'îles de Santorin* ». Publications de l' Académie d' Athènes. T. A. No. 4, 1935, p. 18).

Nous avons aussi rédigé à temps le journal détaillé des phénomènes explosifs observés, de l'éruption du volcan de Kaménis pour toute la période 1925-1926, ainsi que de la parasitaire de celle de 1928, en nous basant d'un côté sur les observations du chef de la Station météorologique de l'Observatoire d'Athènes à Phira, Mr. A. Velouzos, d'autre côté sur nos propres observations, et enfin sur d'autres éléments que nous avons pu recueillir.

A remarquer que les observations de Mr. Velouzos, sous leur forme primitive, ne sauraient être publiées, vu que l'observateur s'y servait de graduations tout à fait subjectives. Toutefois, en tenant compte de nos propres observations au cours de notre séjour à Phira et aussi des explications orales du chef de la Station météorologique, nous avons pu interpréter, avec une grande approximation, les termes employés dans les dépêches envoyées chaque jour par le dit chef à l'Observatoire d'Athènes.

Nous avions remis ce journal à feu le professeur et académicien Mr. C. Kténas, par les soins duquel il devait être compris dans l'étude générale de l'activité du volcan que l'Académie d'Athènes allait publier.

Malheureusement, à cause de la mort prématurée de de ce savant, seule la première des trois parties de cette étude générale à pu être publiée [1]).

Dernièrement la famille de Kténas, ayant trouvé parmi ses papiers le manuscrit de notre journal, qui devait être publié dans une autre partie de l'étude générale, nous l'a rendu.

Pensant qu'il serait dans l'intérêt de la science volcanologique de donner à la publicité ce journal, nous avons jugé utile de demander à Mr. le Professeur F. Signore de faire publier ce travail, si possible, dans le « Bulletin de l'Association de Volcanologie de l'Union Géodésique et Géophysique Internationale ». Mr. Signore a très poliment

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[1]) C. Kténas « *Contribution à l'étude des laves tertiaires et quaternaires de la mer Egée* ». Publications de l'Académie d'Athènes. T. A. No. 4, 1935.

accepté notre demande, ce de quoi nous tenons à le remercier encore une fois ici.

Ce journal ne fait que donner une image plus détaillée de l'évolution des phénomènes explosifs, sans modifier les communications faites jusqu'à présent au sujet des éruptions de 1925-1926 et de 1928 par les divers volcanologues qui s'en sont occupés.

## I — L'éruption de 1925-1926.

1925. Août 11. A $11^h \frac{1}{4}$ (T. de l'E. O.) à peu près une fumée épaisse commença à s'élever du détroit entre Néa-Kaméni et Micra-Kaméni, à l'endroit dit « Kokkina Néra ». Cette fumée devenait de plus en plus épaisse et formait des nuées très opaques, d'une odeur de soufre brûlé.

A $18^h$ environ eut lieu la première explosion : un énorme pin de fumée, chargé de cendres, s'éleva de la mer, accompagné d'un fort bruit et projection de blocs incandescents.

Pendant toute la nuit suivante, il y eut des explosions continuelles, avec détonations de fumée épaisse et de cendres et projection de blocs incadescents. En plus, on entendait, presque continuellement, de forts bruits et un mugissement continu.

12. Dès le matin le volcan était en pleine activité : des explosions continuelles à nuées de fumées, accompagnées de bruit ressemblant à des tonneres ; effusion de lave; projection de blocs incandescents; entre les deux îlots (Néa et Micra Kaméni) apparut une nouvelle formation volcanique (Fouqué Kaméni). Dans l'après-midi le volcan était au même état.

13-14. La fréquence et l' intensité des explosions ainsi que les autres phénomènes sont diminuées ; la nouvelle formation augmente continuellement horizontalement et en hauteur.

15-18. Même état du volcan. La nouvelle formation, continuant à augmenter en dimensions, a occupé le détroit entre Néa-Kaméni et Micra-Kaméni. Dégagement de fumée de quatre points.

19. Même état du volcan. Vers $15^h$ eut lieu une violente explosion : un pin de fumée énorme en hauteur et en largeur est dégagé, accompagné d' un fort bruit et de la projection de blocs incandescents, qui couvrirent le volcan pendant $10^m$.

20. L'explosion violente de la veille ayant cessé, le volcan présentait pendant tout le reste de la journée et la nuit suivante la même activité que pendant le 13-18 d'août.

21. Depuis $5^h$ du matin les bruits étaient très forts et presque continus ; explosions à petits nuées blanches s' élevaient, à cause du calme, à une grande hauteur. Autour des îles Kaménis la mer présentait une coloration rouge-verte.

A partir de midi les bruits sont devenus plus rares et plus faibles ; au demeurant l'activité est la même ; la nouvelle formation a occupé à l' est toute la petite baie « Kokkina-Néra » et s'étend déjà au délà.

De $21^h$ à $23^h$ les bruits devenaient très forts et les explosions étaient accompagnées de la projection de cendres et de blocs incandescents.

22. Même état du volcan ; aucun changement à son explosivité depuis le matin.

23 24 Depuis le matin du 23 août l'activité du volcan présentait une petite rémission.

25. Depuis le matin le volcan est en rémission ; il en sort seulement de la vapeur blanche, rarement en volutes, et sans bruit ; le mugissement était continu.

26. Pendant la nuit explosions à nuées de fumée avec des blocs incandescents, accompagnées de bruit ; le mugissement était toujours continu.

Pendant le jour on constata une augmentation appréciable de l' activité du volcan ; on entendait continuellement le mugissement ; on voyait sortir de la fumée opaque en volutes avec des blocs incandescents et des bruits.

27. Pendant toute la nuit précédente et la journée du 27 l'activité du volcan continua avec la même intensité ; toutefois les pins de fumée étaient plus grands et accompagnés de cendre ; les bruits aussi étaient plus forts ; à partir de $17^h$ l'activité du volcan présenta une petite rémission.

28. L' activité du volcan était très intense pendant toute la journée et la nuit suivante ; de fortes explosions successives ; de grands pins de fumée avec des cendres et blocs incandescents ; les bruits forts et continus ; le mugissement continu.

29. Du matin au soir l' activité du volcan présenta une certaine rémission ; au cours de la nuit tous les phénomènes explo-

sifs recommencèrent avec la plus grande intensité.

30\. L'activité du volcan très intense ; vers $11^h\ 35^m$ une très puissante explosion, la plus violente depuis le commencement de l'activité du volcan ; celui-ci fut couvert d' un grand pin de fumée accompagné d' un bruit effroyable ; les blocs incandescents et les cendres furent projetés jusqu' à l'endroit dit « Pangos ».

31\. Pendant la nuit, jusqu'au matin, l'action du volcan présentait la même grande intensité ; vers $17^h\ 20^m$ il y eut une nouvelle explosion puissante, accompagnée de forts bruits ; des blocs incandescents tombaient jusque dans la mer.

Septembre 1. Pendant toute la nuit du 31 août au 1 septembre il y avait de continuelles explosions avec projection de blocs incandescents, accompagnées de forts bruits.

2\. Depuis le matin on voyait sortir presque continuellement des pins de fumée avec cendres et blocs incandescents, mais les bruits étaient plus faibles ; le mugissement était toujours continu. Pendant toute la journée l'activité était plus intense. Depuis le soir le volcan était en paroxysme.

3\. Activité intense pendant toute la journée.

4\. Depuis le matin on constata une grande augmentation de l' activité du volcan ; explosions continues à grands pins de fumée avec des cendres ; de forts bruits continuels ; un mugissement continu.

6-7. Tous les phénomènes explosifs ont continué avec une grande intensité ; les blocs incandescents lancés par le volcan tombaient dans la mer.

8. Depuis le matin une petite rémission de tous les phénomènes explosifs.
9. Vers 11h ½ recommença l' activité intense du volcan : de 20h au matin du lendemain (sept. 10) elle était encore plus intense que pendant tous les jours précédents ; des explosions continuelles ; d' énormes pins de fumées tout illuminés ; de blocs incandescents tombaient autour du volcan, qui semblait tout embrasé, et aussi dans la mer jusqu' à « Pangos ».
10. Activité moins intense.
11. Tous les phénomènes explosifs présentent une grande intesité, qui s'est conservée pendant toute la nuit jusqu' au lendemain matin.
12. Depuis le matin l' activité intense ordinaire. En plus, depuis la veille on voyait tomber des sables.
13. Pendant toute la journée du 13 septembre les explosions se succédaient presque continuellement, à intervalles de 20 à 30 secondes, et étaient accompagnées de projections abondantes de matières solides (blocs incandescents, sable, cendre) et d'énormes dégagements de gaz et de vapeurs. Des tourbillons de fumée sortaient des fentes du dôme d'éruption et, s'élevant à de grandes hauteurs, formaient au-dessus de l' île de Santorin un épais nuage noir. De ce nuage il tombait continuellement des cendres abondantes, surtout sur le sud de l' île, en raison d' un léger vent NNW, et cette pluie de cendres rendait invisible cette partie de l' île. On entendait presque sans répit des bruits très forts semblables aux é-

clats de tonnerre dans un orage ; de plus, continuels différents sons, parfois rythmiques, depuis le mugissement ou le bruit d'un train qui approche, jusqu'à un simple bourdonnement De petites éruptions ont été observées aussi aux extrémités des deux langues de la nouvelle formation (v. planche).

A partir du coucher du soleil, l'activité du volcan se faisait encore plus intense. Pendant les explosions, le dôme était éclairé par des flammes, et les masses ignées tombaient sur ses flancs ou dans la mer en produisant un bruit caractéristique. Sur toute la surface du dôme on percevait alors de nombreuses fissures entrecroisées, et, à travers ces fissures, on distinguait clairement le magma igné intérieur. La nuit, nous remarquâmes des fissures semblables sur d'autres points de la nonvelle formation, vers les extrémités de ses deux langues.

A $23^{h}$ $05^{m}$ eut lieu une violente explosion sur toute la surface du dôme de l'éruption. Les matériaux projetés verticalement et à une grande hauteur formèrent un immense tourbillon arborescent, à l'intérieur duquel nous observâmes trois décharges électriques et des explosions de bolides (morcellement dans l'air de pierres ignées). Du grand nuage qui s'était formé au-dessus de l'ile, il tomba à Phira une pluie de gros sable noirâtre qui se changea vers le matin en une pluie de cendre. Cette explosion était la plus grande de toute cette période d'activité du volcan.

14. Pendant toute la journée l'activité du volcan continua très intense ; vers $22^h$ $45^m$ il y eut une explosion, semblable à celle du soir précédent pour tous les phénomènes explosifs, mais d'une moindre intensité.
15. Activité un peu plus intense du volcan.
16. De minuit (du 15 au 16 sept.) au matin tous les phénomènes explosifs présentèrent de nouveau une très grande intensité ; ensuite il n'y avait que l'activité intense du jour précédent.
17. Du matin à midi l' activité du volcan était moindre ; dans l'après-midi elle devint assez intense.
18. Pendant toute la nuit précédente et la journée du 18 l'activité du volcan continue assez intense.
19-22. Depuis le matin du 19 jusqu' au soir du 22 le volcan était en rémission ; à partir du soir du 22 activité de nouveau intense.
23-24. L'activité intense continue.
25. Du matin à midi le volcan est en rémission, dans l' après-midi activité un peu intense.
26-27. L'activité intense continue.
28-29. Activité assez moindre.
30. Pendant toute la nuit du 29 au 30 sept. le volcan était en rémission ; mais à partir du matin l' activité intense ordinaire.

Octobre 1-2. Activité un peu intense du volcan.
3. Pendant la nuit du 2 au 3 activité plus intense ; à partir du matin l'activité un peu intense.
4-7. Tous les phénomènes explosifs continuent avec une activité un peu intense.

8. Depuis le matin activité plus intense que de jours précédents de ce mois.
9. Depuis le matin activité assez intense.
10. Du matin à 15h le volcan est plus calme, ensuite présenta une activité un peu intense.
11-12. L'activité un peu intense continue.
13. Depuis le soir du 12 oct. l'activité du volcan est devenue très intense.
14. Depuis le matin l' activité de nouveau un peu intense.
15 Pendant toute la nuit précédente activité plus intense ; à partir du matin l'activité un peu intense.
16-22 L'activité un peu intense continue.
23-25. Activité plus intense que le jour précédent.
26. De 3h-5h activité très intense ; pendant le reste de la journée l'activité un peu intense.
27. L'activité un peu intense continue.
28. A partir de 2h l' activité devenue très intense avec de forts bruits ; par petits intervalles on voit sortir de pètites nuées noires de fumée.
29. La même activité très intense pour tous les phénomènes explosifs continua pendant toute la nuit du 28 au 29 octobre. A partir du matin de ce jour l'activité était un peu intense, et a duré toute la journée ; on voyait continuellement sortir de grandes nuées de fumée noire.
30. Depuis le soir précédent (29 oct.) jusqu'au matin activité très intense pour tous les phénomènes explosifs avec de courtes relaches. Ensuite, pendant toute la journée et la nuit suivante, l'activité

un peu intense, avec sortie continuelle de grandes nuées de fumée.

31. Depuis le matin l'activité était très intense et se conserva pendant toute la journée.

Novembre 1. L'activité très intense, qui a commencé le jour précédent, a continué pendant toute la journée du 1 novembre; continuellement on entendait de forts bruits et l'on voyait de grandes nuées de fumée noire.

2. Depuis le soir du jour précédent l'activité devint un peu intense.

3. Depuis le soir du jour précédent le volcan se trouvait en rémission ; dans l'après-midi l'activité un peu intense.

4. L' activité un peu intense a continué.

5. Depuis le matin, activité plus intense que le jour précédent.

6-9. Même situation que le jour précédent, jusqu'au matin du 9 novembre.

10. Depuis le matin du jour précédent activité plus intense.

11-12. Depuis le matin (11 nov.) l'activité un peu intense.

13. Pendant la nuit précédente (du 12 au 13 nov ) l' activité était plus intense pour tous les phénomènes explosifs ; depuis le matin du 13 nov. l'activité un peu intense.

14. Depuis le soir du jour précédent jusqu' au matin l' activité était plus intense pour tous les phénomènes explosives et elle s' est maintenue telle jusqu' à minuit du 14 au 15 novembre

15-18. L'activité est peu intense.

19. Depuis le matin activité assez intense.

20-21. L'activité est peu intense.

22. L'activité plus intense que d'ordinaire.

23-30. Depuis le matin du 23 nov. l' activité peu intense.

Décembre 1. Depuis le matin activité peu intense.

2. Depuis le matin activité assez intense.

3-6. L'activité assez intense a continué.

7. A partir de minuit activité plus intense que d' ordinaire.

8. A partir de minuit activité peu intense; le soir l'activité intense ordinaire.

9-13. L'activité intense ordinaire a continué.

14-15. Activité peu intense.

16-17. L'activité intense ordinaire.

18-19. Depuis le matin activité un peu plus intense que d'ordinaire.

20. Depuis le soir du jour précédent activité très intense.

21-25. L'activité intense ordinaire.

26-27. Activité plus intense que d' ordinaire.

28-31. Activité intense.

1926 Janvier 1-4. L'activité intense ordinaire.

5 Depuis le matin activité peu intense.

6-8. Activité peu intense.

9-23. Activité intense.

24-25. Activité assez intense.

26. Depuis le matin activité intense.

27-30. Activité intense.

31. Activité assez intense.

Février 1. Activité intense.

2. Vers 20h 40m une assez forte explosion avec un grand bruit ; effusion de lave et projection de blocs incandescents qui ont couvert le volcan.

3-10. Activité intense.

11-12. Le volcan en rémission.

13. Depuis le matin activité intense ; a partir de midi peu intense.

14-28. Activité intense.

Mars. 1-7. Activité peu intense.

8-9. Depuis le matin du 8 mars activité intense.

10-14. Activité peu intense.

15-17. Depuis le soir du 15 mars activité intense.

18-31. Activité peu intense.

Avril Dans l' après-midi du 10 avril activité intense.

Pendant tout le reste du mois activité peu intense.

Mai 1-19. Activité affaiblie ; les bruits et les mugissements ont cessé ; on ne voit qu'un dégagement de fumée par longs intervalles.

Pendant la nuit du 18 au 19 mai une explosion avec projection de blocs incandescents.

20. A $11^h\ 30^m$ une forte explosion : dégagement de fumée avec des cendres sans bruit ni mugissement ; formation d'une grande nuée.

21. Vers $8^h$ formation d' une nuée de fumée de hauteur et d'épaisseur très grandes, sans bruit ni mugissement.

Pendant le reste de la journée et la nuit suivante activité intense ; dégagement de nuées de fumée et projection de blocs incandescents.

22. Depuis le matin activité peu intense.

23. Activité très affaiblie.

Après ce jour le volcan est rentré dans la phase solfatarienne et ainsi s'est terminée l'éruption de 1925-1926.

## II. — L' éruption parasitaire de 1928.

Janvier 22. Ce jour là ont commencé à s' élever, par intervalles, des vapeurs blanches de

la petite branche méridionale de Fouqué Kaméni, située au-dessus du fond de l'ancien chenal de « Kokkina-Néra ».

23. Vers $5^h$, une faible secousse sensible à Phira et vers $22^h$, de la même journée, a eu lieu la première explosion sans détonations ; elle a provoqué la formation d' une petite nuée blanche.

25. Vers $9^h$ $15^m$, une explosion plus violente avec accompagnement d' un faible mugissement ; on a vu s' élever jusqu' à une hauteur d' environ 200 mètres une épaisse colonne de nuées chargées de cendres. Pendant le reste du jour, on voyait, par intervalles, de la fumée blanche à la surface.

26. Le matin une explosion faible à petite nuée blanche jusqu' à une hauteur de 50 m. et vers $20^h$ $30^m$ une autre semblable, à médiocre nuée blanche. Pendant le reste du jour il n' y avait que de la fumée épaisse dégagée de la surface.

27. Vers $7^h$ $40^m$ une explosion à médiocre nuée blanche.
Dégagement continu d'épaisses fumées, par fois avec de très faibles explosions à petites nuées blanches, sans détonations ou mugissements et cendres.

28. Pendant la nuit du 27 au 28 on voyait des flammes, à la surface de la même place (Kokkina Néra). L'explosivité très affaiblie jusqu' au matin du lendemain.

29. Le matin et à $14^h$ deux explosions à médiocre nuée blanche. A $16^h$ $50^m$ a eu lieu une explosion à nuées très opaques, avec des cendres, pendant laquelle la colonne a atteint une hauteur de 300 m ; cette

explosion était suivie de trois autres plus faibles à nuées grises ou blanches, à 17h 05m, 17h 20m et 17h 25m (les nuées se sont élevées jusqu'à une hauteur de 100 m.).

30-31 Explosivité très affaiblie ; rares poussées de vapeurs blanches.

Février 1-3. Toute exhalaison était presque suspendue.

4-6. Dans la nuit du 3 au 4 février petites explosions répétées à nuées blanches, dont les plus grandes relativement étaient accompagnées de cendres. Cette période d'activité explosive, beaucoup plus faible que celle du mois précédent, a continué, en s'affaiblissant progressivement, jusqu' au soir du 6 février, pendant laquelle ont été observées deux explosions à nuées blanches avec des cendres et des lueurs à la surface du volcan.

7. Le matin quelques petites explosions à nuées blanches avec des cendres, touchant la surface du volcan.

8-27. L'explosivité très affaiblie durant depuis midi du 7 février a continué jusqu' au matin du 28 du même mois ; il n' y avait que des fumées blanches à la surface s' élevant par fois à quelques mètres ; une odeur d' hydrogène sulfuré a été signalée, très forte même à Phira, du 12 au 15 février.

28. Depuis le matin a commencé une nouvelle période d'activité explosive ; plusieurs explosions à petites nuées blanches, dont quelques-unes accompagnées d' un faible bruit sourd.

29. Des explosions continuelles à petites nuées blanches avec des cendres ; dans

l'après-midi 5 explosions à nuées epaisses, qui se sont élevées jusqu'à une hauteur de 300 m. avec des cendres.

Mars 1-3. La manifestation explosive ci-dessus est allée en augmentant de violence.

4. A partir de la nuit du 3 au 4 mars des explosions, par petits intervalles, suivies de détonations violentes et de petits blocs incandescents ; la colonne de vapeur atteignait une hauteur de 500 à 800 mètres.

5. Pendant la nuit plusieurs explosions, dont deux très fortes, à $2^h$ et $4^h$, suivies de détonations violentes et de blocs incandescents ; depuis le matin 6 explosions à nuées blanches, suivies de détonations; la colonne de vapeur atteignait une hauteur de 300 à 800 mètres.

6-8. L' activité explosive ci-dessus a présenté quelques affaiblissements.

9. Depuis le matin 4 explosions médiocres à nuées blanches ; pendant la nuit on signale des blocs incandescents.

10. Dans la nuit du 9 à 10 mars l'activité explosive de nouveau assez forte ; plusieurs explosions à nuées blanches médiocres, suivies de détonations et de blocs incandescents.

11. Dans la journée l'explosivité a commencé à s' affaiblir progressivement et à partir du 18 mars toute manifestation éruptive s' est arrêtée.

## III. — Manifestations de l' énergie sismique près des centres volcaniques des Cyclades méridionales de 1925 (Août)-1930.

Après l' entrée du volcan des Kaménis à l' état actif, survenue au mois d'août 1925, jusqu' à la fin de l' année

1930, dans la zône volcanique des Cyclades et spécialement dans les îles de *Santorin* et de *Milo* se produisirent les secousses sismiques ci-dessous, d'un caractère pour la plupart tout à fait local 1).

## 1927

**Milo.** Le soir du 19 *février* deux fortes secousses locales, dont l' une fut enregistrée par les instruments de la Station sismique d' Athènes, et plusieurs autres secousses faibles, de durée très courte et accompagnées de bruit.

**Santorin.** En *novembre*, une secousse locale légère.

Au cours, de l'année 1927, dans l'île de *Sériphos*, située un peu au Nord de Milo, furent ressenties les secousses suivantes, toutes de nature locale, dont la plupart étaient accompagnées de bruit.

En *mai*, une secousse très faible.

En *juin*, 5 secousses faibles, 36 très faibles et 10 légères.

En *décembre*, une secousse légère

## 1928

**Santorin.** En *janvier*, une secousse faible, dont l' origine était dans la mer de Crète, enregistrée à Athènes.

En *mars*, une secousse légère, qui avait son origine un peu vers le SE de l' île, enregistrée à Athènes.

En *décembre*, 5 secousses légères, dont 3 tout à fait locales et 1, enrégistrée à

1) Ces secousses sont comprises dans les « *Catalogues des tremblements de terre ressentis en Grèce* » pendant les années 1925-1930, qui sont publiés dans les Annales de l' Obs. Nat. d' Athènes, T. X et XII.

Athènes, ayant son origine dans la mer de Crète, ressentie aussi à *Milo*.

Pendant la même année furent aussi ressenties à *Sériphos* de nombreuses secousses locales.

En *mars*, 2 secousses légères avec bruit.

En *mai*, vers le soir du 21, une secousse faible et 4 légères avec bruit; de même, jusqu'au matin du jour suivant, 30 autres secousses légères avec bruit.

En plus, le 22 mai furent ressenties 4 secousses légères avec bruit, suivies de 3-4 autres aussi légères jusqu'à minuit de même jour.

Du 22 jusqu'au 30 mai, 2-3 secousses légères furent ressenties par jour, pour la plupart avec bruit, et le 23 de ce mois une secousse faible avec bruit.

En *juin*, 2 secousses faibles, 5 très faibles et 7 légères, toutes locales et avec bruit.

## 1929

**Milo.** Le 18 *janvier*, des secousses locales à différentes reprises, avec bruit.

**Santorin.** Le 28 *janvier* et le 17 *avril*, furent ressenties deux secousses faibles, enregistrées à Athènes, qui avaient leur origine, la première un peu vers le S de l'île de Santorin et la seconde dans la mer de Crète.

Dans la même année, à *Sériphos* le 12 *novembre* une secousse légère locale avec bruit et quelques jours auparavant d'autres secousses très légères.

## 1930

**Santorin.** Le 14 *février*, une secousse très forte, ressentie aussi dans les autres îles des Cyclades du Sud, mais qui avait son épicentre dans la mer de Crète, enregistrée à Athènes.

Le 6 *mars* deux secousses, l'une faible et l'autre légère, enregistrées à Athènes, probablement répliques du tremblement précédent.

**Milo.** Entre 20 et 22 *Mai*, 4 secousses locales légères.

Le 25 *juillet*, une secousse locale faible, enregistrée à Athènes.

Outre ces secousses, d' autres aussi furent ressenties, pendant la période ci-dessus mentionnée 1925-1930, à Milo et à Santorin, mais leurs foyers se trouvaient assez loin de la zone volcanique des Cyclades.

De même, pendant longtemps, d' après certains renseignements, des secousses locales à peine perceptibles étaient ressenties, de temps en temps, à Phira.

Ces dernières secousses devraient, croyons-nous, être attribuées, selon toute probabilité, à des mouvements brusques se produisant dans l' intérieur des laves sorties du volcan, par suite des tensions élastiques se développant dans ces laves par leur refroidissement et contraction progressifs et libérées enfin par le progrès même de ces phénomènes. Par conséquent on devrait appeler ces secousses « *méta-volcaniques* ».

(Institut Séismologique de l' Université d' Athènes).

N. A. CRITIKOS — *Journal des phénomènes éruptifs du volcan des Kaménis (Santorin) de 1925-1926 et de 1928.*

Le volcan des Kaménis (Santorin) après-midi du 13 septembre 1925.

Le Ier février 1938, en sa propriété de Bussy, par Joinville (Haute-Marne), dans la 81ème année de son âge, après quatre ans d'une douloureuse maladie est mort le

**Professeur CHARLES LALLEMAND**

Inspecteur général des Mines, en retraite,
Directeur honoraire du Service du Nivellement général de la France,
Membre et ancien Président de l'Académie des Sciences
de l'Institut de France,
Membre et ancien Président du Bureau des Longitudes,
Ancien Président de l'Union géodésique et géophysique internationale
(1919-1933),
Commandeur de la Légion d'Honneur.

Le Bureau central international de Volcanologie exprima son vif regret pour la perte de l'illustre Professeur à la Famille, à l'Academie des Sciences de l'Institut de France et au Comité National Français de Géodésie et Géophysique.

# CHRONIQUE DE L'UNION GÉODÉSIQUE ET GÉOPHYSIQUE INTERNATIONALE

## ASSOCIATION DE VOLCANOLOGIE

### Septième Assemblée Générale de l'Union Géodésique et Géophysique Internationale

**Washington, 4-15 septembre 1939**

BUREAU CENTRAL INTERNATIONAL DE VOLCANOLOGIE

Pour la correspondance :
Prof. Francesco Signore
Via Tasso, 199 — Tél. 15749
Napoli (Italie)

Naples, juillet 1938

*Mon cher Collègue,*

J'ai l'honneur de vous faire savoir que la Septième Assemblée générale de l'Union géodésique et géophysique internationale aura lieu à Washington le 4 septembre 1939.

Je vous prie de vouloir bien m'envoyer *aussitôt que possible* vos propositions personelles (ou celles du Comité national de Volcanologie par vous éventuellement présidé) pour rédiger l'*Ordre du jour* des séances.

*Chaque thème ou proposition doit être suivi par un abrégé ou dilucidation de l'argument qu'on entende traiter.*

Dans l'espoir que vous serez présent à cette session, je vous prie d'agréer l'assurance de ma parfaite consideration.

Le Secrétaire général
F. Signore

Aux Présidents et Secrétaires des Comités nationaux de Géodésie et Géophysique.

Aux Membres des Sub-comités nationaux de Volcanologie.

# Union Géodésique et Géophysique Internationale

## (International Union of Geodesy and Geophysics)

Dr. **D. La Cour**, Président. — Meteorologisk Institut, Copenhagen. Denmark.

Brigadier **H. St. J. L. Winterbotham**, C. B., C. M. G., D. S. O.
Secrétaire-général. — " Grandfathers „, Broughton, Hants., England.

**Seventh General Assembly**

Copenhagen and Broughton,
April 9, 1938.

To the Representatives of Governments and Organizations Adhering to the International Union of Geodesy and Geophysics, and of All Other Governments and Organizations Interested in Geodesy and Geophysic.

*Gentlemen :*

In accordance with the action taken at the Sixth General Assembly of the International Union of Geodesy and Geophysics, the Seventh Triennial Assembly of that body will be held in Washington, D. C., U. S. A., September 4 to 15, 1939. It is the purpose of this letter to invite you to send delegates of the adhering organizations of your country and representatives of your Government and of your scientific organizations interested in the fields of the Union to this Assembly. You are cordially invited to take active part in this meeting.

For your information, please find attached the First Circular to Delegates and Guests which has been prepared by the American Organizing Committee. The International Union anticipates that this Assembly will reflect in its proceedings the rapidly growing importance and value in human endeavor of geodesy and geophysics, and that it will also further cement and enhance international cooperation so essential to the development of natural resources, as well as to improved knowledge leading to the economic application of geophysical methods of scientific investigation and utility.

It is hoped that your country and its scientific bodies will be well represented.

Sincerely yours,

D. La Cour, *President*

H. St. Winterbotham, *General Secretary*

# American Geophysical Union
## in cooperation with National Research Council

September 4 to 15, 1939

FIRST CIRCULAR TO DELEGATES AND GUESTS [ISSUED APRIL 9, 1938]

### GENERAL

The meetings of the Union and of all its associations will be held September 6 to 15, 1939, at Washington, D. C., U. S. A., chiefly in the buildings of the George Washington University and of the National Research Council and National Academy of Sciences. Optional meetings for associations, their executive committees, and commissions may be held on September 4 and 5, preceding the opening day of the meeting.

A provisional program is attached. It is subject to modification by the later definite requirements of the Union and of its associations within the period set for the Assembly. The American Organizing Committee for the Assembly has been formed to arrange for the reception, accommodation, and entertainment of delegates and guests. Early advice of intention to attend is requested, for which enclosed sheet may be used. Communications relating to matters pertaining to the Seventh Assembly are to be addressed to.

Dr. J. A. Fleming, General Secretary,
5241 Broad Branch Road, Northwest,
Washington, D. C., U. S. A.

### TRAVEL TO WASHINGTON

Delegates and guests will doubtless find their own travel bureaus best suited to inform them fully regarding steamship schedules and rates. American delegates to meetings abroad have found it economical and entirely satisfactory to travel by the one-class boats and on other boats either in the cabin or tourist class. It is important

that reservations be made at as early a date as possible to avoid disappointment in securing passage; there is usually much ocean travel during August and September, and in 1939, because of the two world's fairs in New York and San Francisco, travel will be greater.

Rates of railroad travel in the United States at the present time may be reckoned at 2 cents per mile in ordinary day-coaches. The ordinary day-coaches are generally quite confortable for travel during the day and, on the main railroads, most of these cars are air-conditioned. Fer tickets entitling one to travel on Pullman chair cars and sleepers the rate is 3 cents per mille plus the Pullman charge for chair or berth; all Pullman cars are air-conditioned. Except for special long journeys, such as to the West Coast, there is no reduction for round-trip tickets. Stop-over privileges between points of departure and destination are generally allowed.

For passengers arriving in New York (225 miles from Washington) and in Baltimore (40 miles from Washington) there is excellent hourly service by fast trains on two railroads. Transatlantic passengers arriving in Boston will find a convenient schedule of day and night railroad service of 10 hours to Washington. A railroad journey from Montreal or Toronto to Washington requires about 16 or 17 hours. For transpacific delegates and guests it may be noted that the railroad journey from San Francisco, Los Angeles, or Seattle requires about four days unless transcontinental air-service is used. A table showing typical prevailing railroad and Pullman fares is given at the end of this circular. These fares are subject to change but will give delegates and guests a basis for estimating cost of travel in the United States. There is excellent service for transportation of baggage by the railroads in the United States and Canada, 150 pounds being allowed for each person without charge from railroad station to railroad station. In large cities the railroads provide also for the checking directly from the hotel of departure to the hotel of destination at moderate rates.

## ACCOMMODATION IN WASHINGTON

The American Committee has selected the Hotel Washington as the headquarters hotel for the Assembly. The practice of a headquarters hotel for meetings of societies and organizations is a standard one in the United States and has been found helpful in making for successful meetings and for personal contacts. This hotel is centrally located, within walking distance of the meeting places and of many points of national interest in Washington (see attached map). The Committee has obtained special rates for rooms which will be reserved for the period of the Assembly. For rooms provided with bath, shower, circulating ice water, and telephone service, the rates per day are as follows : Single room at $ 3.00, $ 3.50, and $ 4.00; double room with double bed at $ 4.00, $ 4.50, and $ 5.00: double room with twin beds at $ 5.00 and $ 6.00.

There are a number of other good hotels available. Daily rates for single rooms at these hotels vary from $ 2.00 to $ 9.00 and for double rooms from $ 3.00 to $ 12.00, depending upon the location and type of accommodation.

There are also available near the meeting places private residences where rooms may be had at $ 1.50 per day per person. These rooms do not have all the conveniences, comforts, and services of a hotel. It is believed that satisfactory reservations for delegates and guests who desire such accommodations can be made by the Committee provided requests are received by June 1, 1939.

The Committee will also make reservations upon request at the Hotel Washington or, if desired, at another hotel. Requests for accommodations should state the class of room, number of persons, and rate desired. Early reservations will make it easier to meet the requirements of our delegates and guests.

At the Hotel Washington, continental breakfasts served in the rooms may be arranged for at about 50 cents each. Table d'hote service at that Hotel ranges as follows :

Breakfast, 40 cents to \$ 1.00; lunch, 70 cents to \$ 1.00; dinner, \$ 1.25 to \$ 2.00. A la carte service is also provided. Less expensive service may be had in nearby cafeterias and restaurants. An allowance for meals of from \$ 1.50 to \$ 3.00 per day per person should be reasonable.

At the headquarters hotel there will be available the services of interpreters for French, German, Italian, and Spanish, both at the hotel office and at the telephone switchboard. An attractive feature of the Hotel Washington is its roof-garden restaurant and lounge, with wide-awninged, water-cooled terrace overlooking Washington and affording panoramic views of the Potomac River and nearby Virginia.

## LOCAL TRAVEL

Local travel by public trams (street-cars) and busses anywhere in Washington costs 10 cents per passenger, or a weekly pass good for unlimited use may be purchased for \$ 1.25. Taxicab fares within the city are quite reasonable and at present range from 20 to 70 cents depending on distance.

## CLIMATE AND CLOTHING

Intending visitors should bear in mind that the period set is toward the end of the summer in Washington and that, while the nights should be confortable, some days may be rather warm and humid, and therefore light summer-weight clothing should be provided. On the other hand, clothing such as usually worn at this season of the year in Europe will be required, with top coats for ocean trips, for travel in Canada, and for trips to the West Coast. The temperature in Washington during the first half of September averages from about 60° to 80° Fahrenheit (16° to 27° Centigrade). Extreme ranges have been as great as 40° to 98° F (4°,5 to 37° C). The weather during this period of the year is generally fair, but it will be wise to provide protection against occasional rains and showers.

## GEOPHYSICAL EXHIBIT

A geophysical exhibit will be held at the George Washington University in connection with the Assembly in Washington. National committees are invited to send exhibit material sponsored by national geophysical institutions, delegates, or private firms. The responsibility for packing and carriage both ways and for other charges including insurance during transit and during exhibition must be borne by the exhibitors. Adequate space for exhibits and ordinary tables will be provided. All exhibits should be accompanied by descriptive labels in English and in French. Intending exhibitors should inform the General Secretary of the American Geophysical Union as soon as convenient of their desire to exhibit and should state the approximate space required as well as the size of the exhibits. An appropriate committee will have charge of proper clearance through the customs of shipments of instruments for the exhibit. Further information on this subject will be supplied later.

## MISCELLANEOUS

During 1939 there will be two world's fairs in the United States - one in New York and one in San Francisco. At this date the authorities of both fairs advise that they have no information concerning special rates of reductions to be granted by transatlantic or transpacific steamship companies or by railroads in the United States, although it is quite possible special rates may be in force at the time of the Assembly. Any information that may become available in this connection will be supplied later.

It is hoped that a complete printed list of the delegates and guests may be prepared for distribution by September 6, 1939. To facilitate this work, delegates and guests are requested to send to the General Secretary of the American Geophysical Union at the earliest practicable date information regarding their expected participation in the Assembly together with data regarding offices and

titles, organizations represented, and home addresses. It is hoped it will be possible to include in this list photographs of each representative; delegates and guests are requested to send photographs so that the necessary halftones may be made.

The Pan American Institute of Geography and History is considering an extraordinary assembly of that Institute in Washington during the Assembly of the International Union of Geodesy and Geophysics. The Institute's interest is in geophysics as applied in geography. This would increase the number of delegates and guests from the Western Hemisphere and promote an even wider international cooperation than our Union at present enjoys.

## POSSIBLE TRIPS IN UNITED STATES AND CANADA PRECEDING MEETINGS OF UNION AND OF ITS ASSOCIATIONS

In addition to the general excursions and other entertainment for delegates and guests indicated in the provisional program attached and those special minor excursions of individual associations or jointly by several associations for which arrangements are to be made, three longer trips are proposed. These will blend geophysical work, geology, and scenic travel, and will afford some idea of the extent to which geophysics has been applied in the United States. Delegates and guests are asked to send early information of their wishes as regards these trips in order that appropriate arrangements may be made in due time.

*TRIP NO. 1 from August 29 to September 1, 1939, inclusive (possibly jointly with such Canadian scientific organizations as may wish to cooperate).* From Kingston, Ontario, Canada, to Washington, D. C., U. S. A., via St. Lawrence Valley, Adirondacks, Finger Lake Region of New York, Allegheny Plateau, New York - Pennsylvania natural-gas area, Appalachian Mountains, Juniata and Susquehanna valleys, Harrisburg, Gettysburg, Frederick, and Washington (arriving at Washington about mid-after-

noon). Transportation will be by courtesy of tke American Geophysical Union.

| | |
|---|---|
| Approximate cost, trip No. 1: | |
| Meals and lodging for 4 days . . . . . . | $ 20 |
| Registration fee for arrangements, guides, etc., payable in advance . . . . . . . . | 10 |
| Total per person | $ 30 |

Guests arriving from points in Canada will assemble at Kingston, Ontario, on Tuesday night, August 28. Guests coming from New York will take the train from New York Tuesday night, August 28, and register for the trip at Watertown, New York, the next morning. This group will Join those coming from Canada at Morristown, New York.

*TRIP NO. 2, leaving New York on the afternoon of August 28 and arriving in Washington on the morning of September 4, 1939* — From New York to New Orleans, and area of active geophysical exploration in Gulf Coast Salt-Dome Region, and thence to Washington.

| | |
|---|---|
| Approximate cost, trip No 2: | |
| Railroad fare New York to New Orleans and Pullman berth . . . . . . . . . . . | $ 50 |
| Railroad fare New Orleans to Washington and Pullman berth . . . . . . . . . . . | 40 |
| Expenses en route 2 days and meals and lodging 4 days in field . . . . . . . . | 40 |
| Total per person | $ 130 |

*TRIP NO. 3, leaving New York on the evening of August 17 and arriving at Washington on the morning of September 4, 1939* — This trip will blend geophysical work, geology, and scenic travel. New-York to Yellowstone Park, to Boulder Dam, Grand Canyon of Colorado, Carlsbad Caverns, oil-areas of Texas and Gulf Coast, to New Orleans to Washington.

Approximate cost. trip No. 3 :

| | |
|---|---|
| Railroad fares-New York to Red Lodge, Montana | $ 95 |
| Needles, California, to Grand Canyon, Arizona | 10 |
| Monohans, Texas, to Dallas, Texas . . . | 20 |
| New Orleans to Washington, D. C. . . . | 40 |
| Other travel expenses (3200 miles) . . . . | 95 |
| Meals on train 4 days and meals and lodging on tour 15 days . . . . . . . . . . . | 125 |
| Incidentals . . . . . . . . . . . . . | 15 |
| Total per person | $ 400 |

No organized trips have been arranged to follow the Assembly, but full information and advice will be provided to those who may wish to travel in the United States after the meeting.

## TYPICAL RAILROAD FARES

General note. The information given below is as for April 1938

| BETWEEN | Ordinary daycoach fare | PULLMAN Fare | PULLMAN Chair | PULLMAN Lower berth | Approx. time one way |
|---|---|---|---|---|---|
| | | | | | *hours* |
| Baltimore to Washington . . . | $ 0.80 | $ 1.15 | $ 0.50 | . . . | 1 |
| Philadelphia to Washington . . | 2.70 | 4.00 | 0.75 | $ 2.50 | 2.5 |
| New York to Washington . . . | 4.50 | 6 70 | 1.25 | 2.50 | 4 |
| Boston to Washington. . . . | 10.05 | 14.60 | 2.25 | 3.75 | 10 |
| Pittsburgh to Washington . . . | 6.05 | 9.05 | 1.50 | 2.50 | 6 |
| Chicago to Washington . . . | 15.45 | 23.15 | . . . | 5.50 | 16 |
| New Orleans to Washington . . . | 22.40 | 33.60 | . . . | 8.00 | 30 |
| Houston to Washington . . . | 29.95 | 44.90 | . . . | 10.25 | 48 |
| Toronto to Washington (via Buffalo) | 12.00 | 16.85 | . . . | 3.75 | 17 |
| Montreal to Washington . . . | 13.90 | 19.75 | . . . | 4.25 | 16 |
| Washington to San Francisco or to Los Angeles and return . . . | 95.90 | See note A | | | 96 |
| New York to Boston . . . . | 4.60 | 6.90 | 1.00 | 2.50 | 5 |
| New York to Watertown, N. Y. . | 6.50 | 9.75 | 1.65 | 2.50 | 8 |
| New York to Chicago . . . . | 18.20 | 27.25 | . . . | 6.00 | 18 |
| New York to New Orleans. . . | 26.90 | 40.30 | . . . | 10.50 | 34 |
| New York to San Francisco or to Los Angeles and return . . . | 101.40 | See note B | | | 96 + |
| Quebec to Montreal . . . . | 6.00 | 6.00 | . . . | 2.00 | 5 |
| Montreal to Ottawa . . . . | 3.50 | 3.50 | . . . | 2.00 | 3 |
| Ottawa to Toronto . . . . | 7.50 | 7.50 | . . . | 2.00 | 11 |
| Toronto to Kingston . . . . | 6.00 | 6.00 | . . . | 2.00 | 8 |
| Toronto to Niagara Falls . . . | 3.00 | 3.00 | . . . | 1.00 | 2.5 |

Note A. — Pullman round-trip fare is $ 130.40 plus lower berth $ 20.50 each way, or a total of $ 171.40; tourist-sleeper round-trip fare is $ 114.45 plus Pullman lower berth to/from Chicago $ 5.50 and tourist lower berth $ 8.50 each way, or a total of $ 142.45.

Note B. — Pullman round-trip fare is $ 141.50 plus lower berth $ 21.75 each way, or a total of $ 185.00; tourist-sleeper round-trip fare is $ 125.55 plus Pullman lower berth to/from Chicago $ 6.00 and tourist lower berth $ 8.50 each way, or a total of $ 154.55.

# International Union of Geodesy and Geophysics
# Union Géodésique et Géophysique Internationale

## Seventh Triennial General Assembly at Washington 1939
## Septième Assemblée Générale Triennale à Washington 1939

PROVISIONAL PROGRAM [ISSUED APRIL 9, 1938]
PROGRAMME PROVISOIRE [EMIS LE 9 AVRIL 1938]

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### MONDAY, SEPTEMBER 4 - LUNDI, 4 SEPTEMBRE

10:00-13:00
- (a) Optional meetings of association commissions before the General Assembly
- (a) Séances facultatives des commissions des associations avant l'Assemblée Générale
- (b) Registration of delegates and guests
- (b) Inscription des délégués et des invités

14:30-16:30 Idem

### TUESDAY, SEPTEMBER 5 - MARDI, 5 SEPTEMBRE

10:00-13:00 Idem
14:30-16:30 Idem

### WEDNESDAY, SEPTEMBER 6 - MERCREDI, 6 SEPTEMBRE

10:00-13:00
- (a) Meetings of Executive Committees of the Union and of associations
- (a) Séances des Comités Exécutifs de l'Union et des associations
- (b) Optional meetings of association commissions before the General Assembly
- (b) Séances facultatives des commissions des associations avant l'Assemblée Générale
- (c) Registration of delegates and guests
- (c) Inscription des délégués et des invités

Afternoon Registration of delegates and guests
Après-midi Inscription des délégues et des invités

*

| | |
|---|---|
| 20:30 | First General Assembly and reception (full dress)<br>Première Assemblée Générale et réception (tenue de soirée) |

THURSDAY, SEPTEMBER 7* - JEUDI, 7 SEPTEMBRE*

| | |
|---|---|
| 10:00-13:00 | Association meetings [Presidential address - Geodesy]<br>Séances des associations [Discours du Président - Géodésie] |
| 14:30-16:30 | Association meetings [Presidential address-Seismology]<br>Séances des associations [Discours du Président-Séismologie] |
| 17:00 | Formal opening of exhibit and tea<br>Ouverture officielle de l'exposition et thé |

FRIDAY, SEPTEMBER 8 - VENDREDI, 8 SEPTEMBRE

| | |
|---|---|
| 10:00-13:00 | Association meetings [Presidential address-Meteorology]<br>Séances des associations [Discours du Président-Météorologic] |
| 14:30-16:30 | Association meetings [Presidential address-Terrestrial Magnetism and Electricity]<br>Séances des associations [Discours du Président-Magnetisme et Electricité Terrestres] |
| 20:30 | Public lecture<br>Conférence publique |

SATURDAY, SEPTEMBR 9 - SAMEDI, 9 SEPTEMBRE

| | |
|---|---|
| 10:30-13:00 | Association meetings<br>Séances des associations |
| Afternoon<br>Après - midi | Automobile trip in and around Washington<br>Excursion en automobile dans Washington et ses environs |

SUNDAY, SEPTEMBER 10 - DIMANCHE, 10 SEPTEMBRE

| | |
|---|---|
| | All-day automobile trip to Annapolis<br>Excursion en automobile à Annapolis (toute la journée) |

MONDAY, SEPTEMBER 11 - LUNDI, 11 SEPTEMBRE

| | |
|---|---|
| 10:00-13:00 | Association meetings [Presidential address-Oceanography]<br>Séances des associations [Discours du Président- Océanographie] |
| 14:30-16:30 | Association meetings [Presidential address-Volcanology]<br>Séances des associations [Discours du Président-Volcanologie] |
| 20:30 | Reception and dancing (full dress with decorations)<br>Réception et danse (tenue de soirée avec décorations) |

TUESDAY, SEPTEMBER 12* - MARDI, 12 SEPTEMBRE*

| | |
|---|---|
| 10:00-13:00 | Association meetings [Presidential address-Hydrology]<br>Séances des associations [Discours du Président-Hydrologie] |
| 14:30-16:30 | Association meetings<br>Séances des associations |

WEDNESDAY, SEPTEMBER 13 - MERCREDI, 13 SEPTEMBRE

| | |
|---|---|
| 10:00-13:00 | Association meetings<br>Séances des associations |
| Afternoon<br>Après-midi | Minor excursions for associations<br>Petites excursions pour les associations |
| 2:30 | Public lecture<br>Conférence publique |

THURSDAY, SEPTEMBER 14* - JEUDI, 14 SEPTEMBRE*

| | |
|---|---|
| Morning | Joint meetings of associations or commissions and minor excursions of associations |
| Matinée | Séances communes des associations ou des commissions et petites excursions pour les associations |
| Afternoon | Idem |
| Après-midi | Idem |
| 20:00 | Smoker and conversazione<br>Smoker et conversazione |

FRIDAY, SEPTEMBER 15 - VENDREDI, 15 SEPTEMBRE

| | |
|---|---|
| 10:00-11:00 | Final association meetings<br>Dernières séances des associations |
| 11:00-13:00 | Final General Assembly<br>Dernière Assemblée Générale |

* Ladies will be specially entertained on days so marked.
* Diversions spéciales pour les dames les jours ainsi indiqués.

If you propose to attend the Washington Assembly, please fill in the following particulars, indicate accomodation and travel arrangements (striking out irrelevant matter), and return as soon as possible to

Dr. J. A. Fleming, General Secretary,
5241 Broad Branch Road, N. W.,
Washington, D. C., U. S. A.

# International Union of Geodesy and Geophysics

## Seventh general assembly, Washington, 1939

Name ..............................
(in capital letters)
Address ..............................
(in capital letters)
Accompanied by ..............................
(names in capital letters)
..............................

..............................

Probable date of arrival in Washington ..............................
Probable date of departure from Washington ..............................
Port of arrival (if known)

### ACCOMMODATIONS WANTED

I desire that reservations for single (double) room with double (twin) bed for ... persons be made for me at the headquarters hotel, Hotel Washington, at rate not exceeding $......... per day.

I desire that reservations for single (double) room with double (twin) bed for ... persons be made for me at another hotel at rate not exceeding $......... per day.

I desire that reservations for ..... rooms for ..... persons be made for me at a private residence at rate not exceeding $.......... per day.

### TRAVEL ARRANGEMENTS WANTED

I desire that tentative reservations be made for me and for .... others in connection with pre-Assembly Trip No. ....., as described in the First Circular.

Other information desired concerning travel facilities

..............................

..............................

..............................

..............................

INTERNATIONAL GEOLOGICAL CONGRESS
XVIII SESSION — GREAT BRITAIN, 1940

General Secretary: GEOLOGICAL SURVEY AND MUSEUM,
EXHIBITION ROAD, LONDON, S.W. 7

REGISTERED TELEGRAPHIC ADDRESS
Inland Telegrams: **Incongeol, Southkens, London**
Foreign Telegrams & Cables: **Incongeol, London**

le 19 juillet 1938.

Signor **Francesco Signore**
Bulletin Volcanologique
Via Tasso, 199
Naples.

*Monsieur*,

Nous avons l'honneur de vous envoyer ci-joint copie d'une circulaire que nous sommes en train de distribuer, au sujet de la XVIII Session du Congrès International Géologique. Le Congrès aura lieu à Londres en 1940. Nous vous serions fort reconnaissants si vous vouliez bien faire annoncer brièvement le Congrès dans votre Journal.

Veuillez agréer, Monsieur, avec nos remerciments anticipés, nos salutations les plus sincères.

W. F. P. McLintock
W. B. R. King
*Secrétaires.*

# INTERNATIONAL GEOLOGICAL CONGRESS
# EIGHTEENTH SESSION — GREAT BRITAIN, 1940

## FIRST CIRCULAR

London, *July, 1938*

On behalf of the General Organizing Committee we have the honour to bring to your notice that the Eighteenth Session of the International Geological Congress will be held in Great Britain during 1940 on the invitation of the Geological Society of London, which was accepted by the Bureau of the Seventeenth Congress in Moscov, 1937.

1. This invitation is the outcome of a strong desire on the part of the Fellows of the Geological Society of London ad of British geologists in general to reciprocate the hospitality received by them on so many occasions in other countries, and to fulfil the wish, which they know has been widely expressed at recent sessions, that the Congress, which last met in Great Britain in 1888, should meet again in this country.

2. The General Organizing Committee are glad to be able to state that the active co-operation of the Officers of the Geological Survey has been officially recognized and sanctioned, and that permission has been obtained from the Department of Scientific and Industrial Research to establish the office and headquarters of the Congress in the building of the Geological Survey and Museum, South Kensington, London, S. W. 7.

3. The General Organizing Committee are pleased to report that the financial support necessary for the proper organization of the Congress has been secured, and the Committee and the Council of the Geological Society of London desire to express their sincere thanks to the societies and institutions, industrial organisations and individual donors whose generous response to the appeal for funds issued by the Geological Society has rendered the issue of an invitation possible.

4. At a special meeting called by the Geological Society of London and attended by representatives of kindred societies, public bodies and personal donors to the Congress funds, it was decided to entrust the preparation and organization of the Congress to a General Organizing Committee. It was also decided to vest the executive authority of the General Organizing Committee in an Executive Committee and to recommend to the Bureau of the Congress that the Officers of the General Organizing and Executive Committees be the Officers of the Congress. These Committees were unanimously elected. It was further agreed that the power to add to the membership of the General Organizing Committee and the Executive Committee be vested in the Council of the Geological Society of London.

The following have been elected to membership of the General Organizing Committee and the Executive Committee in accordance with the above-mentioned resolutions, and have consented to serve: —

## GENERAL ORGANIZING COMMITTEE

### HONORARY PRESIDENT

Sir William Bragg, O. M., K. B. E., President of the Royal Society.

### OFFICERS

*Vice-Presidents*

The President of the Geological Society of London.
The Director of the Geological Survey of Great Britain.

*General Secretaries*

Dr. W. F. P. McLintock, Deputy Director of the Geological Survey of Great Britain.
Prof. W. B. R. King, University College, London.

*Treasurer*

F. N. Ashcroft, Esq., 1 Egerton Gardens, London, S.W. 3.

## EXECUTIVE COMMITTEE

### OFFICERS

| | |
|---|---|
| *General Secretaries* | Dr. W. F. P. McLintock.<br>Prof. W. B. R. King. |
| *Treasurer* | F. N. Ashcroft, Esq. |

DATE OF THE CONGRESS

5. The general sessions of the Congress will be held in London from July 31 st to August 8 th, 1940, a time which will permit of the excursions before, during and after the session being conducted under the most favourable circumstances for travelling and accommodation.

MEMBERSHIP OF THE CONGRESS

6. The conditions of Membership of the Congress are outlined in Paragraph 8 of the Rules adopted by the Thirteenth Congress held in Brussels in 1922 :—

« No professional title is required to support a request to register. Nevertheless, the excursions organized before and after the session will be more especially reserved for the members of the Congress who are Geologists, Geographers, and Mining Engineers and for other persons who devote themselves to the study or practice of some branch of Geology ».

MEMBERSHIP FEE

The Membership Fee for the Eighteenth Session of the Congress has ben fixed at £ 1 10s. 0d.

SUBJECTS FOR DISCUSSION

7. The subjects proposed for consideration by those attending the Congress are detailed below. Offers of papers on these subjects and suggestions for additional subjects for discussion are cordially invited, and should be submitted as soon as possible to the General Organizing Committee through the General Secretaries.

1. Magmatic Differentiation.
2. Metasomatic Processes in Metamorphism.
3. Caledonids in North-west Europe.
4. Rhythm in Sedimentation.
5. The Geology of Iron-Ore Deposits.
6. The Geology of Coal Seams.
7. The Geology of Petroleum.
8. The Geology of Sea and Ocean Floors.

9. The Stratigraphical Limits of the Ordovician System.
10. The Pliocene-Pleistocene Boundary.
11. The Distribution of Early Vertebrates.
12. Faunal Facies and Zonal Correlation.
13. Earth Movements and Evolution.
14. The Geological Results of Applied Geophysics.

## EXCURSIONS

8. The excursions to be offered have not been finally determined, and the list given below is subject to change. The date, duration and scope may be revised, and other excursions may be offered in addition to, or in place of, those listed.

### A. EXCURSIONS BEFORE THE CONGRESS

The following excursions have been provisionally selected to take place before the Congress, and will last from 7 to 14 days each (one 21 days).

A.1. The West Highlands and Islands of Scotland (most systems from Pre-Cambrian onwards; Caledonian tectonics: Devonian and Tertiary igneous phenomena). 21 days approximately; by steamer or equivalent motor-coach transport.

A.2. The North of England, including the Lake District (mainly Lower Palæozoic). 14 days approximately.

A.3. The Pennines (Carboniferous). 8 days approximately.

A.4. South Wales and the Bristol district (mainly Palæozoic). 10 days approximately.

A.5. The Isle of Wight and Dorset (Mesozoic and Tertiary strata; tectonics). 12 days approximately.

A.6. Economic deposits (coal, ironstone, cement materials, slate, brick-earth, gypsum, etc.). 10 days approximately.

A.7. Cornwall and Devonshire (mineralogical). 7 days approximately.

It is also probable that an independent excursion to East Anglia will take place before the Congress, under the auspices and organization of the International Quaternary Union.

### B. SHORT EXCURSIONS DURING AND NEAR TO THE DATES OF THE CONGRESS

It is hoped to arrange a series of short (half day and day) excursions during the Congress to places of geological and general scientific interest in and around London, and

also a series of short (2 to 3 days) excursions immediately prior to and after the session of the Congress. Details of these will be issued in a later circular.

C. EXCURSIONS AFTER THE CONGRESS

The following excursions (7 to 14 days each) have been provisionally selected :

C.1. A general excursion through England. 14 days approximately.
C.2. The Nort-east of Ireland Dublin district (Pre-Cambrian to Tertiary), arranged in conjunction with representatives of Eire. 14 days approximately.
C.3. The East Coast of the Scottish Highlands (metamorphic rocks, Caledonian intrusions, Old Red Sandstone) 8 days approximately.
C.4. The Lowlands of Scotland (Ordovician to Carboniferous strata ; volcanic and intrusive igneous rooks). 8 days approximately.
C.5. The Midlands, Yorkshire, Cumberland, Lancashire, North Wales (glacial geology). 10 days approximately.
C.6. North and Central Wales and the Welsh Border (mainly Lower Palæozoic). 14 days approximately.
C.7. South Wales and the Bristol district (Carboniferous). 7 days approximately.
C.8. Devon and Cornwall (Hercynian Chain, granites, mineral veins). 10 days approximately.
C.9. East Anglia (with emphasis on the Mesozoic and Pliocene rocks). 7 days approximately.

COST OF EXCURSIONS

It is not possible to state definitely the cost of any of the proposed excursions at this juncture, but it is not anticipated that the cost per day will exceed £ 1 0s. 0d. to £ 1 5s. 0d., inclusive of railway and/or motor-coach transport, except in the case of the excursion to the West Highlands and Islands of Scotland, where it is expected that the cost per day may be about £ 1 10s. 0d.

PARTICIPATION IN THE EXCURSIONS

As is customary, the General Organizing Committee, acting through the Executive Committee of the Congress, reserves the right to limit the number of persons taking part in any of the excursions and to select participants in excursions without regard to priority of application. The decision of the Committee in these matters shall be final.

## SCIENTIFIC COMMUNICATIONS

9. Details of the arrangements to be made relative to the presentation of papers submitted for reading will be announced in later circulars.

## GENERAL

10. It will considerably facilitate the work of the Committee if those planning to attend the Congress and the excursions will fill in the enclosed form (A)*, so far as it is possible for them to do so at the present time, and return it to the General Secretaries at an early date. This form is not to be regarded as an application for membership of the Congress nor for participation in the excursions, and its completion and return in no way binds the sender or places him under any financial or other obligation. The form is intended to aid the Committee in its work and to insure that those who contemplate attending the Congress shall receive all subsequent circulars. A form to be used on application for membership and for participation in the excursions will be issued later.

The Committee will be grateful if the recipients of this circular will bring it to the notice of any person who has not received it but is likely to be interested in the Congress or its programme.

Further circulars wiil be issued at later dates which will contain additional details and record progress in the development of the plans for the Congress

Inquiries or proposals concerning the work of the Session or the future activities of the Congress should be addressed to the General Secretaries.

* Omis.

## CORRESPONDENCE

11. All communications should be addressed to the General Secretaries, Eighteenth Session, International Geological Congress, Geological Survey and Museum, Exhibition Road, South Kensington, London, S.W.7.

The Telegraphic Address of the Eighteenth Session of the Congress is :—

For Inland Telegrams: Incongeol, Southkens, London.
For Foreign Telegrams and Cables: Incongeol, London.

On behalf of the General Organizing Committee:

W. F. P. McLintock,
W. B. R. King,

*General Secretaries.*

# SOMMAIRE

## Notes, mémoires et rapports de Volcanologie

[illegible]